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# Electron Physics

BY

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WITH A FOREWORD BY

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# FOREWORD

For a student beginning the study of physics, a series of experiments in the laboratory is recognized as being of great help in giving a content to new terms and in illustrating new relations. In studying the various branches of modern physics, however, the student has usually had to get along without this assistance, although the new concepts and ideas required are more detached from ordinary experience than in the case of classical physics. In this volume on *Electron Physics*, Dr. Hoag has described experiments that may be performed with simple apparatus and without the expenditure of too much time and care. In carrying out experiments, a student is brought to recognize the terms and theories used in describing the phenomena he has observed, as natural and necessary abstractions from his own experience. The book should also aid in the cultivation of the art of experimentation in this field, by interesting the student in the beautiful and wonderful phenomena which he may study. Anyone with any taste for experimental physics will be fascinated in watching the discontinuous changes of velocity of an oil drop in a condenser, as it picks up various charges, or in observing the luminous path of a beam of electrons as its curvature is altered by a magnetic field. Such satisfaction in the observation of phenomena is as important in the development of an experimental physicist as the appreciation of the relations and connections of the mathematical theories which explain the phenomena. May the book prove useful in initiating many into this fascinating branch of physics.

A. J. DEMPSTER

THE UNIVERSITY OF CHICAGO

# PREFACE

The student of physics, whether beginning or advanced in the subject, is continually confronted with a host of words belonging to the world of modern physics such as, "electron," "alpha, beta and gamma rays," "X-rays," "cosmic rays," "three-electrode vacuum tubes," "photoelectric effect," etc. So far as the author is aware, no book has yet been published which gives carefully prepared outlines of methods by which the student can, for himself, repeat the experiments dealing with all of these concepts. The material is too widely scattered in magazines and books and tends to be either too advanced and detailed or so much simplified as to be misleading. It has, therefore, seemed wise to present at this time a book which would give a simple statement of the concepts, accompanied by experiments which allow a reasonable degree of accuracy and yet are free from the more cumbersome details of the original methods. The book has been prepared for the student who has had one year of college physics or its equivalent. Practically no calculus is used.

The underlying motive in *Electron Physics* is to present evidence for as many of the concepts of modern physics as fall within the scope of the subject chosen.

The book has been arranged so that each chapter is a unit, containing a general treatment of the subject, the important discoveries, definitions and experiments. This is followed by several detailed outlines of experiments which the student may make in connection with the general subject matter. Many points of laboratory technique have been woven into these experiments while the procedure to be followed and the apparatus used have been greatly simplified over the original research methods. Thus the oil drop method for measuring the charge of an electron, which ginally occupied an entire room, may now be performed on a small table. Several of the experiments, in their modified form, are published here for the first time.

The figures, equations and experiments have been numbered chapter by chapter. Thus figure seven-four (7–4) is the fourth

figure in Chapter 7, while equation C–2 is the second one in Appendix C. The list of sixty problems at the end has been found of great assistance to the student in grasping the subject matter. The numerical values in the tables at the end are as nearly up to date as possible.

*Electron Physics* is the outgrowth of a laboratory course in "Radioactivity and Discharge Through Gases" given at the University of Chicago for many years. The course was organized by Professor A. J. Dempster and presented by him until 1925. Since that time the author has been in charge of the course but Professor Dempster has continued to give invaluable advice, suggesting improvements and new experiments. He has aided in the preparation of this book by reading all sections and pointing out changes wherever necessary. It is only through his generosity that the book is to be published under my name alone.

In addition to the thanks due to Professor Dempster, the author is indebted to the other members of the faculty here at Ryerson for occasional advice and to the group of students in years past who have so eagerly tested and rearranged the experiments. The author has greatly appreciated the care and patience shown by Mr. E. J. Davis in preparing the majority of the drawings and the careful reading by Mr. L. C. Beers of the manuscript and proof.

It is always true that there are errors in the first edition of a book of this character. The author will greatly appreciate having these called to his attention.

J. Barton Hoag

The University of Chicago
August, 1929

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# CHAPTER 1

## THE PASSAGE OF ELECTRICITY THROUGH GASES AT ATMOSPHERIC PRESSURE

**Introduction.**

When electricity passes through a gas many new phenomena are observed which do not exist for metallic conduction. Ohm's law is valid in only a few limited cases. New charges of electricity may be created at various points along the gaseous path and the emission of light is a familiar occurrence. It is as though the slender wires were greatly enlarged and illuminated so that the details can be studied not only along the length of the path but at the various parts of a given cross section. The particles of the gas are in rapid motion, some are charged while others are neutral, some drift slowly under an applied potential, others rapidly, and collisions of oppositely charged particles often result in neutral particles. The amount of electricity which passes, and hence the conductivity, change markedly with the pressure of the gas. These phenomena and many others are to be studied in the chapters of this book.

**Sparking.**

At atmospheric pressure a gas, such as air, is a very poor conductor of electricity unless the potential is very high. Ordinarily to break down the resistance requires thousands of volts. Then a great surge of electricity occurs, accompanied by a brilliant flash of light. The potential needed to cause sparking depends on the shape of the electrodes, the gas between them and their distance apart. This phenomenon offers a means of measuring high potentials in terms of the length of a spark gap (see table 2).

**Ionization.**

However, a gas may be made slightly conductive for low potentials by many methods. For example, when a flame is brought near a charged electroscope, charges of opposite sign, which are in the gas, move to the leaves, neutralize their charge and cause them to collapse. These charges may be filtered out by passing the air

from the flame through a glass, wool or cotton plug in a metal tube (Fig. 1–1) or through a long narrow tube. These experiments indicate that the charges diffuse readily to the walls of bodies very close to them. The charges may also be filtered out by passing the gas between two charged metal plates. The process of rendering a gas a conductor of electricity is called ionization and may be accomplished in a variety of ways. For example, $X$ in figure 1–1 may be a source of X-rays, ultra-violet light, a hot filament or the radiations from radioactive substances.

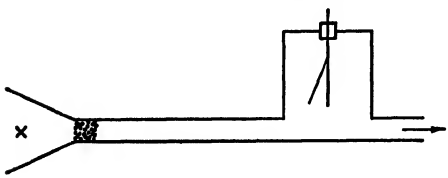


FIG. 1–1. The conductivity of gases.

A more detailed study of the charged particles, called ions, may be accomplished by ionizing the gas between two parallel plates.

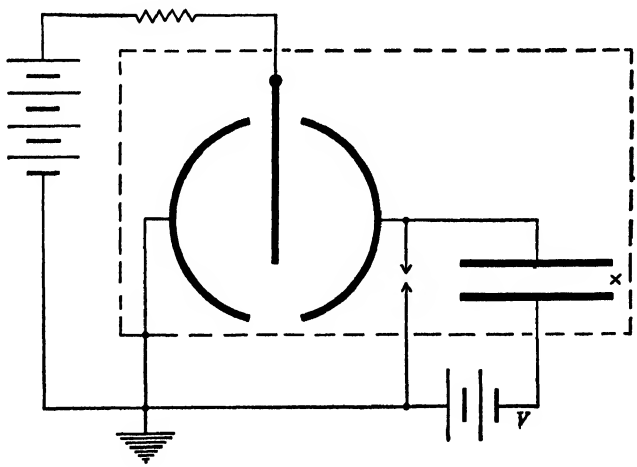


FIG. 1–2. Connections for studying ionization currents.

The plates are charged to various potentials and the flow of current (of ions) between them is observed with an electrometer (Fig. 1–2). The curve in figure 1–3 results. This curve of ionization current ($i$) and potential ($V$) will be considered in three parts. The first part is $OA$ where the current rises as the voltage is increased. When the gas is ionized by the source $X$ (Fig. 1–2) both positive and nega-

tive particles are produced. With no potential between the plates, these move about at random, occasionally passing near an opposite charge when *recombination* to form a neutral particle may take place. Occasionally some may *diffuse* to the plates.

When, however, a potential is applied, the charged particles move, the positive to the cathode and the negative to the anode. The electrometer then shows a current made up of these two streams. Recombination and diffusion still take place and the shape of the curve $OA$ depends on the relative importance of these two factors and on the velocity of the particles.

When all ions which are formed in the gas are being drawn to the plates, a further increase in the potential cannot increase the

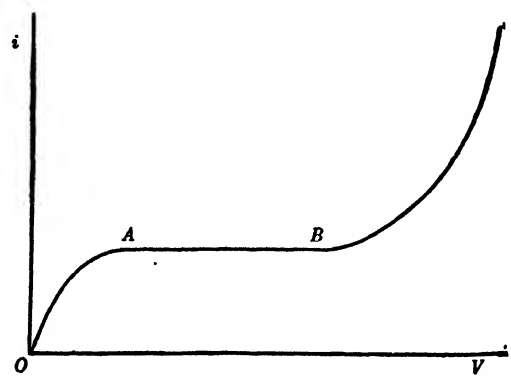


FIG. 1–3. Ionization currents and applied potentials.

current. This *saturation current* is represented by $AB$, figure 1–3. Since this is a measure of the total number of ions produced by the source at $X$ it gives a measure of the strength of the source. Thus the intensity of X-rays, radioactive substances, etc., can be measured. The use of currents below the saturation point, i.e., along $OA$, will obviously give erroneous results since they do not represent the total number of ions produced by the source, and the recombination rates may be different in different cases.

The potential which must be applied across the plates of the ionization chamber in order to insure saturation is different in different experiments but may be roughly stated as between 50 and 200 volts per centimeter for ions produced by the beta and gamma rays of radioactive substances. In these cases, the ions are pro-

duced uniformly in the gas in the ionization chamber, but with alpha particles the ions are produced in high concentration along a narrow beam. Rapid recombination results, requiring the use of several thousand volts per centimeter to give saturation. Further, the potential necessary to produce saturation depends on the density and kind of gas being ionized, the distance between the plates and the presence of dust or moisture. However, if the saturation current is given in amperes per volt per cubic centimeter of air at standard pressure and temperature, it is an accurate specification of the intensity of the source of ionization.

If, now, the potential is still further increased the particles travel with greater and greater velocities (particularly the negative charges) until they acquire sufficient energy to break up neutral atoms at a collision. Thus new positive and negative charges are formed which also move under the applied field and increase the current. This is represented by the curve to the right of *B* in figure 1–3. This rapid increase continues until, with rising potential, a brush discharge or spark occurs. These large currents cannot be measured with the electrometer. As it is difficult to observe ionization by collision at atmospheric pressure, it is better to partially evacuate the region between the plates.

Finally, it is to be noted that the curve does not rise sharply from the saturation value when ionization by collision sets in. This is due to the fact that not all the particles are traveling with exactly the same velocity. Some are moving faster and some slower than the majority.

There are three general ways in which ionization may be produced:

1. By direct impact by moving positive or negative charges.
2. By electromagnetic radiation such as X-rays, ultra-violet light or gamma rays.
3. By heat or thermionic emission.

In order to learn more of the nature of ions, we shall now study in greater detail their recombination and mobility.

**Recombination.**

This is measured by the rate of decay of the ionization after the ionizing source has been removed. Since the charges are in motion,

they do not all recombine at the same time. Rutherford has determined the rate of recombination in several cases by the following method.

A gas is passed at a known rate through a metal tube as is

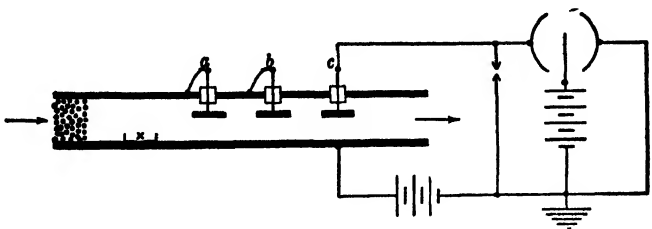


FIG. 1–4. The measurement of recombination rates.

shown by the arrows in figure 1–4. All ions are filtered out by a cotton plug as the gas enters the tube. The gas is then ionized by a radioactive source at $X$. During its passage down the tube, recombination is taking place so that the number of ions existing at $a$ is greater than the number at $b$, which, in turn, is greater than the number at $c$, as indicated by the saturation currents measured with an electrometer. From these readings and the time required for the gas to pass between the electrodes $a$, $b$ and $c$, the rate of recombination is calculated.

It is found that the number $(dn/dt)$ of recombinations each second is approximately the same for different gases and decreases as the pressure is reduced. It is proportional to the square of the number of ions of one kind present at a given time in a unit volume and represents the number of collisions of ions which result in recombination to form neutral particles. The value of $dn/dt$ so found for oxygen is $1.6 \times 10^{-6} \times n^2$, whereas for uncharged particles the kinetic theory gives the number of collisions per second per cc. as $1.25 \times 10^{-10} \times n^2$. It is concluded that, due to electrical attractions, the number of collisions resulting in recombination is 10,000 times greater than the number of collisions between neutral particles.

**Mobility.**

The mobility of an ion is defined as its velocity in centimeters per second under an accelerating potential of one volt per centi-

meter. This is the average velocity of drift of the ions due to the electrical field and it is superimposed on the irregular kinetic motions of the charged particles.

Two schemes for measuring the mobility of ions will now be given. The first is a modification of the Rutherford alternating current method. The ions are produced in a gas in the region immediately above a metal gauze $B$ (Fig. 1–5) by some ionizing source such as a radioactive substance at $X$. Some of these are drawn upward to the metal plate $A$ by the fixed potential $v$, while those of opposite sign are drawn to the gauze $B$ and pass through its meshes into the region above the metal plate $C$. On applying an alternating potential between $B$ and $C$ (by means of the commutator $D$) these ions are attracted or repelled from $C$ each half cycle. The procedure is to adjust the voltage $V$ (maximum value), the frequency of the applied potential and the distance $BC$ until a current is first observed in the electrometer $E$. Under these conditions the velocity of the ion is such that it can just travel the distance $BC$ during one half cycle.* Knowing the distance the ion travels in a known time, its actual velocity and also its velocity under unit field may be calculated.

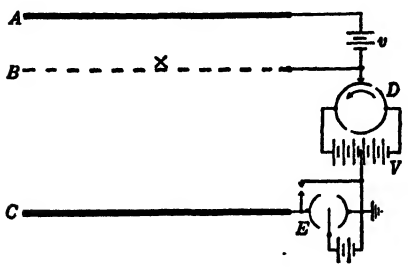


FIG. 1–5. The measurement of the mobility of ions.

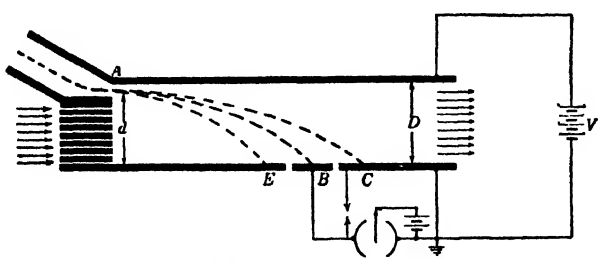


FIG. 1–6. Erickson's method of measuring the mobility of ions.

The second method is that used by Erickson. The ionized gas is introduced into a high-velocity, uniform air current at the point

* This assumes that the accelerating potential has a square wave form.

$A$ (Fig. 1–6). As the ions are carried along they are deflected to the metal plate $EBC$ by means of the high voltage $V$. A small part $B$ of this plate is insulated from the rest and connected to an electrometer. The ions with high mobility will fall at $E$ and those with low mobility will reach $C$. The time ($t$) for the particles to travel from $A$ to $B$ is obtained from the velocity of the air current which is determined by means of a pitot tube. Their actual velocity under the electrical field in the direction $d$ is given by $v = d/t$ and their velocity under unit field is given by

$$k = \frac{v}{V/D} = \frac{dD}{tV}$$

centimeters per second per volt per centimeter.

The mobility of "old" ions in dry air is 1.4 for the positive and 1.8 for the negative and for most gases the positive ions move more slowly than the negative. However, for freshly formed positive ions in air, the mobility is just as great as for the negative. It cannot be definitely stated at this time whether the ordinary ion consists of one or many charged atoms or molecules. The mobility of ions is inversely proportional to the pressure over wide ranges and is independent of the inertia of the ion. In certain gases such as hydrogen, helium, nitrogen and mercury vapor, the electron formed by ionization remains free. The mobility of electrons is very great, ranging from several hundred to many thousand centimeters per second per volt per centimeter. In other gases (the electro-negative) such as oxygen, chlorine and water vapor, the electron attaches itself to a neutral molecule and forms a negative ion.

## EXPERIMENT 1-1

### IONIZATION CURRENT MEASUREMENT WITH A QUADRANT ELECTROMETER

The purpose of this experiment is to observe the current through a gas with various accelerating potentials.

A quadrant electrometer is well suited to this purpose. A discussion of the adjustment and precautions to be taken is given in Appendix A which should be read at this time by the student. A deflection of 1000 millimeters per volt increase of potential may readily be obtained on a scale at a distance of one meter and, since

the capacity of the quadrant and connection may be as small as 50 electrostatic units, a deflection of one centimeter per minute is caused by a current of only $10^{-14}$ amperes. In other words, the quadrant electrometer readily measures the small currents set up in an ionized gas. In fact, the currents may be so great that the needle moves too rapidly for accurate measurement, in which case it is necessary to add a small capacity in parallel with the ionization chamber.

*Precautions.* — For precision work, always time the deflections over the same scale divisions and keep the needle potential constant. Further, it is necessary to place a grounded metal shield around the grounding key and the ionization chamber and to ground the case of the electrometer. Otherwise the readings will be masked by the natural leak of the instrument.

*Experiment.* — 1. Connect as shown in figure A–5 of Appendix A. Adjust the electrometer in the fashion described in the experiment at the end of that appendix. If a Dolezalek electrometer is used, raise the needle to a potential of 100 volts ($V$). (If the lighting circuit is 110 volts D.C., this may be used for rough work.)

2. Ionize the air between the metal plates $A$ and $B$ by placing a small amount of radioactive substance (RaE tubes) on $A$, or by some other convenient means.

3. Make the accelerating potential ($v$) 2, 4, 6, 12, 20, 40, 80 and 160 volts in succession and raise the key $K$ to measure the relative currents. Do not let the maximum rate of deflection exceed one centimeter in five seconds. Test whether the rate of motion of the needle is uniform. There are usually irregularities at the beginning of the deflection so that comparisons should be made by observing the time for the spot of light to pass over from 2 to 5 centimeters after the needle has begun to move steadily.

4. Plot the rates of deflection as ordinates and the accelerating potentials as abscissæ.

5. If the ionization chamber can be evacuated, reduce the pressure to about 2 centimeters of mercury by means of an oil pump and measure the ionization currents while increasing the potential on the plates until ionization by collision is clearly observed. Plot this data as before.

## EXPERIMENT 1-2

### MEASUREMENT OF THE ABSOLUTE VALUE OF AN IONIZATION CURRENT AND THE CAPACITY OF AN ELECTROMETER SYSTEM

1. Connect the instrument as in figure A–5 of Appendix A and adjust as described in experiment A–1. Place a small amount of radioactive substance, whose ionization current is to be measured, in the chamber $AB$.

2. Observe the time $t_1$ for a deflection of say 10 centimeters.

3. Connect a standard condenser of capacity $C_0$ in parallel with the ionization chamber and, using the same source of ionization, observe the number of seconds $t_2$ for a deflection over the same scale divisions.

4. Measure the voltage $v$ which must be applied directly to the quadrants to give the same deflection.

5. Calculate the capacity of the quadrant system ($Q' KB$) from equations A–11 and A–9. Also calculate the value of the ionization current using equation A–8. If $C_0$ and $v$ are in electrostatic units and the time in seconds, the current will likewise be in these units.

6. If a condenser standardized for induction coefficients is available, use the method of Harms for determining the capacity of the quadrant system.

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# CHAPTER 2

## THE ELECTRON

**Introduction.**

The granular structure of electricity has been observed in widely different fields of physics by many different methods. For example, the ions discussed in the preceding chapter carry a charge which is always an integral multiple of a certain small amount. Again, the separate charges emitted by a hot filament consist of one or more of these unit amounts, regardless of the material making up the filament, its temperature or the surrounding gas. The particles spontaneously emitted by radioactive substances carry either one or two times this small amount. Further, frictional electricity such as that on drops of water or oil sprayed from an atomizer is found to have this granular structure.

The name "electron" was first applied to the natural unit or *smallest amount of electricity* found in nature, in 1891 by Professor G. J. Stoney. Since that time the original meaning has been altered until today it is often used in connection with the *particles* in vacuum tubes, or with certain particles emitted by radioactive substances which carry a negative charge of this amount. It is a common constituent of all atoms. Many models of the arrangement and motion of these electrons in the atoms of various elements have been proposed and utilized in the discovery of new laws and properties of nature. In this chapter, methods of measuring the charge of the electron will be presented.

The product of the charge of the electron ($e$) and Avogadro's number ($N$, the number of particles in one gram-molecule of a substance) is a universal constant and has been determined with great accuracy. From this product and a separate measurement of $N$ or $e$, the remaining quantity may be calculated.

**Determination of $N \cdot e$ by Electrolysis.**

Early in the nineteenth century, Faraday studied the passage of electricity through solutions and stated, as one of the laws of electrolysis, that the amount of substance liberated at an electrode

is directly proportional to the quantity of electricity sent through the liquid. Further, he found that the amount liberated from different solutions by the same quantity was not the same. For example, the same quantity of electricity which deposits 1.008 grams of hydrogen will deposit 107.88 grams of silver from any silver solution. Since the atomic weights of hydrogen and silver are as 1.008 is to 107.88 (and from other similar cases), Faraday was able to assert that a certain definite quantity of electricity is always associated in electrolysis with a definite amount of matter.

One electromagnetic unit of electricity (ten coulombs) passing through a standard silver solution, will deposit 0.0111800 grams of silver. This quantity has been determined with great accuracy so that the ratio of charge to mass for silver is also a precise number. Then

$$\frac{E}{M} \text{ for silver} = \frac{1}{0.011180} = 89.45 \frac{\text{e.m.u.}}{\text{gram}}$$

where $E$ is the quantity of electricity associated with $M$ grams of the substance. In other words, 894.5 coulombs will deposit one gram of silver in the usual electrolysis apparatus. 9649.4 electromagnetic units will deposit one gram-molecule (107.88 grams) of silver. Further, 9649.4 e.m.u. per gram-molecule is a universal constant. For example

$$\frac{E}{M} \text{ for hydrogen} = 9573 \ \frac{\text{e.m.u.}}{\text{gram}}$$

so that $9573 \times 1.008 = 9649.4$ is the number of electromagnetic units of electricity passed through a solution in order to liberate 1.008 grams (one gram-molecule) of hydrogen.*

It is now assumed that all the electricity passing through the solution is carried by the ions and that it is distributed in equal amounts on the various ions, that is, each of a large number of ions carries the same small charge. In considering one gram-molecule

* For substances having the same valency, the masses deposited by a given current are proportional to the atomic weights of the substances. For different valencies, the amount deposited is proportional to the atomic weight divided by the valency. This would be expected if an ion of a bivalent substance carries twice the charge of an ion of a monovalent substance.

of any substance, there will be $N$ molecules (Avogadro's number) each carrying the same charge ($e$). Then

$$Ne = 9649.4 \text{ e.m.u.} = 28948 \times 10^{10} \text{ e.s.u.}$$

which is a universal constant. The charge $e$ is that originally designated as one electron by Stoney.

Calculations of the product $Ne$ for gaseous ions have been made from a derived relation between this quantity and the measurable mobilities and diffusion rates of ions. Although not offering the same precision as the measurements in electrolysis, the two values are in good agreement.

It is interesting at this point to indicate the relative masses of the hydrogen ion in solution and the cathode rays in a vacuum tube. The ratio of charge to mass for the hydrogen ion is 9573 electromagnetic units per gram, for silver it is 89.45 and for heavier elements it is still smaller. Since hydrogen is the lightest element known, the value of $E/M$ for any other element must not exceed 9573 unless an ion is found which carries a greater charge than that on the hydrogen ion or has smaller mass, or both. It will be shown later that the ratio of charge to mass for cathode rays in a vacuum tube is $1.77 \times 10^7$ e.m.u. per gram and that their individual charges are the same as for the hydrogen ion. The conclusion is that the particles in cathode rays have a smaller mass than the hydrogen ion in solution. This ratio is $\frac{1}{1849}$.

**Determinations of Avogadro's Number ($N$).**

Avogadro's number ($N$) has been determined by kinetic theory methods which chiefly involve the viscosity of the gas. The rough values so obtained lie between $2 \times 10^{23}$ and $20 \times 10^{23}$.

$N$ has been obtained from a study of Brownian movements. When examined under a high power microscope, it is found that the small particles suspended in a fluid (smoke particles in air, for example) are moving rapidly in a random fashion. These particles are composed of clusters of atoms or molecules and their motion, which is one of the best evidences of the vibrations taking place in gases, is due to an unbalanced bombardment of the particle by many molecules of the fluid. Taken over a sufficiently long time interval the number of gas molecules striking one side of the particle would equal the number striking the opposite side but during

a short time interval the chance bombardment is sometimes greater on one side than on the other. Hence the particle is knocked back and forth in a tortuous path. This motion is always present; it is the same for various particles of different nature but appropriate size, and is not influenced by outside vibrations or currents in the fluid. Einstein's equation for the average distance $\overline{\Delta X}$ which a particle moves in a given direction during time $t$ is

$$\overline{\Delta X}^2 = \frac{2RTt}{NK}$$

where $R$ is the gas constant per gram-molecule ( $= 8.315 \times 10^7$ ergs/degree), $T$ is the absolute temperature, $N$ is Avogadro's number and $K$ is the resistance to the motion as determined by the viscosity of the gas and the size of the particle. The value so deduced is $N = 6.8 \times 10^{23}$ from which $e$ was found to be $4.26 \times 10^{-10}$ e.s.u.*

Due to Brownian movements, small particles may be found supported against the force of gravity when in a suitable suspension. Just as the density of the air in the earth's atmosphere varies with the distance above the surface, so also the number of particles in a suspension increases toward the bottom. The form of the law is the same in both cases, but the apparent mass of the particle in a suspension is appreciably less than the true mass because of the buoyant effect of the fluid displaced. The equation which expresses the number of particles per cubic centimeter at different heights is

$$n = n_0 \epsilon^{-\left[\frac{Nm}{RT}\left(1 - \frac{d}{D}\right)gh\right]}$$

in which $n_0$ is the number per cubic centimeter at a given distance $h$ below the plane in which $n$ is measured, $m$ is the true mass, $D$ the density of the particle, while $d$ is the density of the fluid, $g$ the acceleration of gravity, $R$ the universal gas constant, $T$ the absolute temperature and $N$ the quantity sought, i.e., Avogadro's number. Perrin found for $N$ the value $6.82 \times 10^{23}$. Substitution in the equation $Ne = 9650$ gives $e = 1.415 \times 10^{-23}$ e.m.u. $= 4.24 \times 10^{-10}$ e.s.u.†

* These are not to be considered as the latest values.

† This is not to be considered as an exact value.

Avogadro's number has been measured with precision by a method involving the use of X-rays. A direct measurement of the wave-length of X-rays may be made using a reflection grating, as in the case of light. This is possible since the index of refraction of the speculum metal of the grating is less than unity for X-rays, as shown by A. H. Compton. Hence, X-rays which strike the polished parts of the grating at a sufficiently small glancing angle (30′ or less) will be reflected and diffracted to produce a spectrum. From the known distance between the rulings on the grating and the position of the spectral lines, their wave-length may be measured directly with great accuracy.

The wave-length ($\lambda$) of an X-ray is measured by the method described above. This same ray is reflected from a crystal of calcite and the usual Bragg formula, $n\lambda = 2d \sin \theta$, is used to obtain the grating space ($d$) of the crystal. $n$ is the order of the line (1, 2, 3, etc.) and $\theta$ is the angle of diffraction. In this way an accurate value of the grating space is obtained.

Consider, now, a cubical crystal of rock salt as made up of many elementary cubes with alternate sodium and chlorine atoms at the corners. Let the crystal weigh 58.454 grams (one gram-molecule, $M$), which is the sum of 22.997 grams of sodium and 35.457 grams of chlorine. It will then contain $N$ atoms of each or $2N$ atoms in all. Along each side there will be $\sqrt[3]{2N}$ atoms, each at a distance of $d$ centimeters from the next. The length of each side will then be $d\sqrt[3]{2N}$ and the volume of the crystal will be $d^3 \cdot 2N$. By definition, the density $\rho$ of the crystal is its mass divided by its volume, so that

$$N = \frac{M}{2\rho d^3}$$

A similar equation may be obtained for calcite ($CaCO_3$), where the elementary space lattice is a rhombohedron or distorted cube. To allow for the distortion, a factor $\phi(\beta)$ is included in the denominator. For calcite: $M = 100.07$, $\rho = 2.7102$, and $\phi(\beta) = 1.09630$.

J. A. Bearden has found for the wave-length of the $K_\alpha$ line of copper a value of 1.5422 and for $K_\beta$, 1.3926 angstroms. Using these values, the grating space of calcite is found to be 3.035 $\times 10^{-8}$ centimeters. The value of $N$ is then calculated, and found to be

$$N = 6.022 \times 10^{23}$$

molecules per gram-molecule. From this and the known product of $N$ and $e$, one obtains

$$e = 4.804 \times 10^{-10} \text{ e.s.u.} \pm 0.009$$

**The Charge on the Alpha Particle.**

Certain radioactive substances, radium for example, spontaneously throw out positively charged bodies called alpha particles. The measurement of their charge consists in determining the total charge carried by a known number of particles as described in Chapter 7. Thus, one gram of radium C emits $3.45 \times 10^{10}$ alpha particles each second having a total charge of 32.9 e.s.u. The charge on each is then equal to $9.54 \times 10^{-10}$ e.s.u. When averaged with determinations made with other sources, it is found that the alpha particle carries just twice the now accepted charge of the electron. However, this charge is positive, not negative.

**Cloud Expansion Method of Measuring the Charge of the Electron.**

Consider a gas containing water vapor, in a chamber. Let this be suddenly expanded by pulling out a piston at one end. This expansion causes a cooling below the dew point and water drops are formed on any dust or electrically charged particles which may be present. This appears as a cloud which slowly settles to the bottom of the chamber. Let all the dust be removed by repeated expansions. Then a cloud will not appear unless the gas be ionized, say by a beam of X-rays. Assume that one water drop forms on each ion. Measure the total charge of the cloud as it settles on a plate connected to an electrometer. Measure the weight of the cloud by passing the air through drying tubes. The average weight of one drop can be calculated from Stokes' theoretical law for the velocity of fall of a small body through a gas. By dividing the total weight of the cloud by the weight of each drop, the number of ions is found. Finally, dividing the total charge of the cloud by the number of ions gives the charge on each. Early work gave this as $e = 3.4 \times 10^{-10}$ e.s.u., differing somewhat from the now accepted value.

**Balanced Drop Experiment.**

An electrically charged drop of water may be balanced between two charged metal plates (figure 2–1), the force of gravity downward being counterbalanced by an electrical attraction upward.

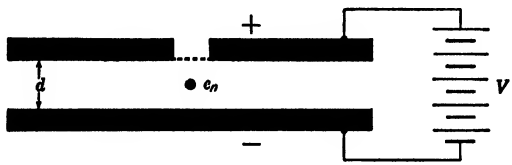


FIG. 2–1. Measurement of the electrical charge on small drops.

The plates must have smooth surfaces and be parallel to each other. The water is charged as it is sprayed from an atomizer, and falls through small holes in the center of the top plate. Air currents must be carefully avoided. The electrical field is then applied, in one direction or the other, so as to prevent the continued fall of the drop. If $e_n$ is the total charge on the drop and $F$ the field strength between the plates, then, when the drop is stationary, the upward electrical force $Fe_n$ is equal to the downward gravitational force $mg$. $m$ is the mass of the drop and $g$ the acceleration of gravity. The field strength is given as the potential (*P.D.*) divided by the distance ($d$) between the plates. Then

$$e_n = \frac{mgd}{P.D.} \tag{2–1}$$

Here $d$ can be measured with micrometer calipers, *P.D.* with an electro-static voltmeter and $m$ by observing the velocity with which the drop falls freely under the action of gravity alone. Stokes' law gives this velocity as

$$v = \frac{2ga^2\sigma}{9\eta} \tag{2–2}$$

where $a$ is the radius of the drop, $\sigma$ the density of the drop and $\eta$ the coefficient of viscosity of the gas through which the drop is falling. From this law the radius $a$ is computed and used in the equation for the mass of the drop,

$$m = \left(\frac{4\pi a^3}{3}\right)\sigma \tag{2–3}$$

assuming the drop to be a sphere of volume $4\pi a^3/3$.

By repeated measurements $e_n$ is found to consist of integral multiples of the value $4.65 \times 10^{-10}$ e.s.u. (which is nearly equal to the now accepted value) and hence the drop carries 1 or 2 or 3 or more electrons.

**The Oil Drop Method.**

Instead of using water for the drop, Millikan used oil to prevent evaporation with consequent loss of weight. Also, instead of balancing the drop he observed its velocity of fall $v_1$ under the action of gravity alone and its velocity of rise $v_2$ under a strong electrical field. It is found that these velocities are directly proportional to the forces acting. Then

$$\frac{v_2}{v_1} = \frac{Fe_n - mg}{mg} \tag{2–4}$$

where the upward electrical force $Fe_n$ acting on the charge $e_n$ is greater than the downward gravitational force $mg$ acting on the mass $m$. From this

$$e_n = \frac{mg}{F}\left(\frac{v_1 + v_2}{v_1}\right) \tag{2–5}$$

The mass of the drop is determined as before from equations (2–2) and (2–3) and it is noted that $F = P.D./d$, as in the balanced drop experiment. However, the law for the velocity of fall requires a correction for small spheres or low pressures. In place of equation (2–2) we have

$$v_1 = \frac{2ga^2\sigma}{9\eta}\left(1 + \frac{b}{pa_c}\right) \tag{2–6}$$

where $b$ is a constant and $p$ is the pressure of the gas. An approximate value for $a_c$ can be determined from equation (2–2) for use in the correction term $b/pa_c$ without materially affecting the result. Thus, for the correction term,

$$a_c = \sqrt{\frac{9v_1\eta}{2g\sigma}} \tag{2–7}$$

Equation 2–6 is now solved for $a$,

$$a = \left(\frac{9\eta v_1}{2g\sigma(1 + b/pa_c)}\right)^{\frac{1}{2}} \tag{2–8}$$

A value for $m$ is obtained by substituting this in equation 2–3 and this, in turn, is used in equation 2–5. Finally, converting the *P.D.* from e.s.u. to volts by dividing e.s.u. by 300, we obtain

$$e_n = \left[400\pi d\sqrt{\frac{1}{\sigma g}\left(\frac{9\eta}{2}\right)^3}\right]\left(\frac{1}{1 + b/pa_c}\right)^{\frac{3}{2}} \frac{(v_1 + v_2)\sqrt{v_1}}{V} \text{ e.s.u.} \qquad (2\text{–}9)$$

For convenience in the experimental work described at the end of this chapter, the meaning of the symbols used in this equation will now be repeated; $d$ is the distance in centimeters between the inside faces of the plates, $\sigma$ is the density of the oil, $\eta$ is the coefficient of viscosity of air (= 0.0001823 at 23° C., 76 cm. of mercury), $g$ is the acceleration of gravity in centimeters per second per second, $b = 0.000617$, $p$ is the barometric pressure of the gas in centimeters of mercury, $a_c$ is the approximate radius of the drop in centimeters computed from equation 2–7, $v_1$ is the velocity of free fall of the drop in centimeters per second, $v_2$ is the velocity of rise under the combined forces of the electrical field and gravity and $V$ is the potential difference in volts between the two plates. The term in brackets is a constant for a given apparatus, which simplifies the calculations.

The value of $e_n$ so obtained is found to be an integral multiple of

$$e = 4.770 \times 10^{-10} \text{ e.s.u.} \pm 0.005$$
$$= 1.590 \times 10^{-19} \text{ coulombs.}$$

From this and the value $Ne = 9649.4$ e.m.u.

$$N = 6.064 \times 10^{23} \pm 0.006$$

**The Shot Effect.**

Consider the emission of negative electricity from a hot filament, $F$ of figure 2–2, sealed in a highly evacuated tube. By charging the metal plate $P$ positively with the battery $B$, a steady flow of current $i$ may be observed with a milliammeter. If this current could be examined with a sufficiently sensitive instrument and over sufficiently short time intervals, it would be found to vary slightly in a random fashion around the average value read on the milliammeter. Further, these variations are not uniform, but occur in jerks and can be used to set up oscillations in the inductance-capacitance circuit $LC$ by "shock excitation." This results in a fluctuating voltage across the capacity $C$. The frequency is given by the natural period of oscillation of the $LC$ circuit.

From statistical considerations, Schottky has derived the following equation, based on the assumption that electricity leaves

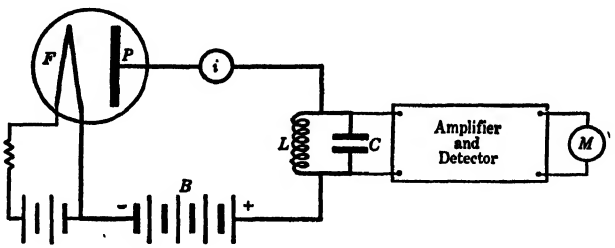


FIG. 2–2. Connections for measuring the charge of cathode particles.

the filament in discrete amounts of charge $e$ rather than in a continuous stream:

$$e = \frac{2RC\overline{I^2}}{i}$$

in which $R$ is the resistance of the inductance and $\overline{I^2}$ is the mean-square value of the fluctuating current in the $LC$ circuit. This latter is determined in terms of the voltage fluctuations across $C$, which are amplified, detected and recorded by the meter $M$. The amount of each negative charge leaving the filament is found to be $1.591 \times 10^{-19}$ coulombs which is the same as that of the electron. Hence, the cathode rays from a hot filament in a vacuum consist of electrons.

The "lumpiness" of the electricity emitted from a hot filament sets a limit to the amplification possible with these vacuum tubes. With extremely high amplification, the shot effect may be heard as a noise in a pair of phones, sounding much like the static in a radio set. This would obviously mask any feeble signal passed through the same amplifier.

It must be mentioned that in determining $e$ by this method, the voltage of the $B$ battery must be sufficiently high that all electrons emitted by the filament are drawn over to the plate, leaving no "space charge" in the vacuum. If such a charge does exist, incorrect values of $e$ will be obtained which will vary from one-third to one-fiftieth of the normal amount.

Furthermore, an additional effect is observed if the natural frequency of the $LC$ circuit is comparatively low. For normal shot

effect this frequency lies in the radio range. For example, Hull and Williams used 750 kilocycles, (400 meters wave-length). For frequencies from 25 to 5000 cycles, the observed effect becomes from 100 to 1000 times as great. This is known as the "flicker" effect and is attributed to the varying surface conditions of the filament.

### EXPERIMENT 2–1

### TO MEASURE THE CHARGE OF AN ELECTRON

The thick metal plates $P$ and the bakelite separating strips $B$ of figure 2–3 must be carefully constructed so that the distance

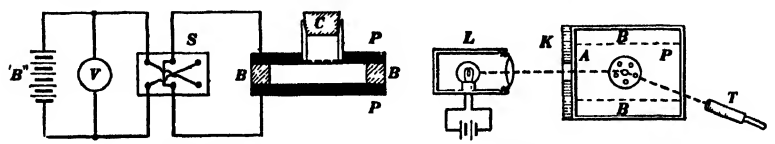


FIG. 2–3. Measurement of the charge on oil drops.

between the inner faces of the plates is everywhere the same. If this is not true, the potential gradient will alter from place to place and the oil drop will drift out of the focus of the observing telescope $T$. The plates may be two or more inches square and four or five millimeters apart. Greater separations may be used but the necessary accelerating voltage will then be rather high (see discussion later on). Air currents are cut off by a celluloid covering around the edges of the plates, all cracks being sealed with cement (Du Pont household). A cardboard screen $K$ having a hole or vertical slit is fastened over the side adjacent to the focusing flashlight $L$ in order to provide a black background in the corner $A$.

Removing the cork $C$, drops of oil are sprayed from an atomizer through small holes in the top plate and observed as bright spots of light by the telescope $T$. A finely divided scale in the eyepiece of the telescope may be such that one division is equal to 0.2 mm. This is to be calibrated by comparison with a tenth millimeter scale set up at the focus, before or after the experiment. The focus must not be changed during the experiment but the whole telescope may be moved slightly if the drop is found to be drifting

out of focus. The plates must be made strictly horizontal to prevent this drifting. Also, if the lamp is placed too close to the plates, its heat will set up convection currents in the air which produce the same effect. This may be reduced by placing a water cell between the two.

It is sometimes difficult to locate the drop at first because of eddy currents of air set up when the oil is sprayed in and the cork replaced. It is advisable to hold the atomizer some distance above the holes while spraying. It will also be of assistance to insert a small wire through the central hole in the upper plate and to focus the telescope on this. Be sure to remove this wire before applying the potential.

The voltage may be produced by radio "B" batteries. Voltages between 20 and 180 will be found sufficient for the apparatus described above.

If the plates *P* have greater separation, say 1.2 cm.,* a higher voltage will be required. This may be obtained as in figure 2–4. *D* is a

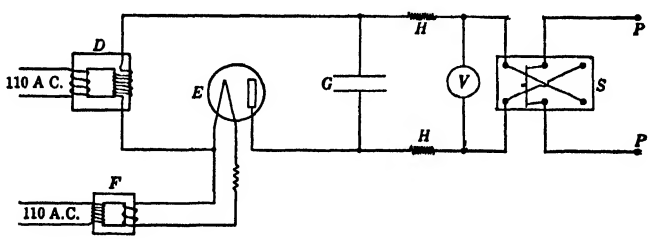


FIG. 2–4. Source of high voltage for the oil drop experiment.

step-up transformer operating on 110 volts AC whose secondary voltage on open circuit is between 500 and 1500 volts. The filament of the rectifying tube *E* may be heated either by a storage battary or by a step down transformer *F*. A U.V.216 tube has been used for *E* without breaking down, since the current drain is very small. The condenser *G* is used to smooth out the pulsating direct current and must be capable of standing the full voltage without puncturing. Three 2 mfd. telephone condensers in series have been found satisfactory. Choke coils need not be added to smooth out the voltage since the current used is very small. The resistances *H* are used to protect the experimenter from the high voltage and the equipment from short circuits. They may consist of about a foot of distilled water in a glass tube or of 48,000 ohm lavites. They must then be larger (8 cm. radius).

$S$ is a special reversing switch which allows the upper plate to be made either positive or negative. It short circuits the plates while in its intermediate position to allow the oil drop to fall freely under the action of gravity alone. This is accomplished with a bar of spring brass which connects the blades of the double-pole double-throw switch while it is being thrown from one position to the other.

The voltage $V$ is read on a good, high resistance, D.C. voltmeter when using the arrangement of figure 2–3. For the higher voltages of figure 2–4, a Kelvin electrostatic voltmeter may be used since it draws no current.

### PROCEDURE — AN EXAMPLE

1. Record the constants. $d = 0.43$ cm., $g = 980$ cm. per second, $\sigma = 0.9199$ gr. per c.c., $\eta = 0.0001823$, $b = 0.000617$, average barometric pressure during the experiment $p = 73.9$ cm. Hg.

2. Calibrate the telescope. One small division = 0.02 cm. Do not change the focus of the telescope during the remainder of the experiment.

3. Adjust the telescope, plates and lamp until a fine wire inserted in the central hole is clearly in focus. Remove the wire.

4. Hook up the apparatus.

5. Remove the cork $C$ and spray a small amount of oil into the vertical tube. Replace the cork gently. Choose an oil drop which moves slowly under the electrical field and under the force of gravity. Can you see any Brownian movement? Follow this drop for at least half an hour while recording the voltage and the time for the drop to move up and down over a given number of divisions. $t_1 = 75.8$ sec. (average fall under gravity over 30 small divisions), $t_2 = 45.0$ sec. Hence $v_1 = 0.00395$ cm. per sec., $v_2 = 0.00667$ cm. per sec. $V = 20.3$ volts.

6. Compute the approximate radius of the drop from equation 2–7. $a_0 = 5.98 \times 10^{-5}$ cm.

7. Compute the charge on the oil drop from equation 2–9. $e_n = 114.3 \times 10^{-10}$ e.s.u.

8. It will be found that the velocity $v_2$ of the drop under the electrical field undergoes sudden changes occasionally. This is due to its picking up or losing one or more electrons. For example, the drop may start out with five electrons, lose three in succession

and then gain them back again. This process may be aided by lowering a bit of radioactive substance, (Ra E tubes) at *C* for a short time. Calculations in (5) were made on the average time $t_2$ of a number of readings of nearly the same value. Using similar averages we obtain $e_n$ = 69.8, 77.0, 80.2, 85.3, 88.9, 96.1, 100.0, 103.5, 110.3, 114.3 $\times 10^{-10}$ e.s.u.

9. Determine the least common divisor of the values of $e_n$. The oil drops above carried 15–24 charges at various times. Dividing the values of $e_n$ by these integers gives $e$ = 4.66, 4.81, 4.72, 4.74, 4.68, 4.81, 4.76, 4.77, 4.80, and 4.76 $\times 10^{-10}$ e.s.u.

10. Average all values of $e$. $e = 4.75 \times 10^{-10}$ e.s.u. Correct value is $4.770 \times 10^{-10}$ e.s.u. Error = 0.43%.

11. If desired, the charges gained or lost by the oil drop may be computed from the differences in the velocities $v_2$ between the averaged groups. These values will also be found to be integral multiples of the charge of an electron.

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## CHAPTER 3

## THE EMISSION OF ELECTRICITY FROM SOLIDS

**Introduction.**

It is necessary to distinguish between two phenomena when a current of electricity passes through a gas. The current may be due to charged particles which have come from some outside source, it may be due to a movement of the ions produced in the gas itself, or it may be a combination of these two effects. If a small amount of radium is placed in an electroscope, the leaves will collapse, chiefly because of a neutralization of their charge by the ions created in the gas and not because of the charged particles themselves which have been emitted by the radium. Thus the total current is sometimes largely due to the gaseous ions. In other cases the two effects may be of approximately the same magnitude. For example, a wire heated by an electrical current and located in a gas at a few millimeters pressure, sends out charged particles which may be drawn over to a charged metal plate. When the filament is first heated, the particles are usually positively charged but this is only a temporary condition. After a short time and always at high temperatures, the particles are negative. During the passage of the particles through the gas, they may collide with the gas molecules and create additional charges. The total current is the sum of the original charges from the hot wire and the gaseous ions. It is difficult to interpret the phenomena when the two effects are present at the same time. In this chapter the emission of charged particles from various bodies is to be studied.

Obviously, the simplest way of avoiding ionization by collision is to remove the gas. For this purpose, a filament and plate are sealed in a glass bulb and evacuated to a high degree. (See figure 3–1.) During the pumping out, gases are given off by the metals and by the walls of the glass bulb. To aid in removing these adsorbed gases, the filament, plate and bulb are heated as hot as possible for several hours. The bulb is finally sealed off at a pres-

sure around $10^{-7}$ millimeters of mercury which will be considered a perfect vacuum in the following discussions. The evacuation is often aided by volatilizing or "flashing" a small amount of "getter" such as magnesium or phosphorous at the time of sealing off. Such a "two-electrode vacuum tube" may be used as a rectifier of alternating currents since the flow of current through it can only take place in one direction. The charges emitted by the filament are negative electrons so that the plate must be charged positively before this valve can pass a current.

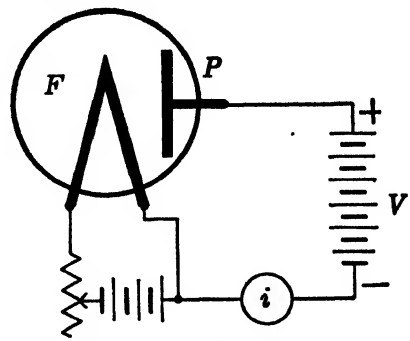


FIG. 3–1. A two-electrode vacuum tube.

Charged particles may also be obtained from cold surfaces subjected to electron bombardment or to ultra-violet light. This latter is known as the *photo-electric effect* while the former is spoken of as *secondary emission*.

**Richardson's Equation.***

The current of electricity which passes from the hot filament to the cold plate in a two-electrode tube may be varied by changing the temperature of the filament or the potential ($V$) of the plate. Increasing either of these will increase the current (as read on the milliammeter $i$) up to a certain saturation value.

Let the voltage $V$ be made sufficiently great to draw over to the plate all electrons emitted by the filament, even at its maximum operating temperature. Then the relation between these *saturation* currents ($i_s$) and the temperature of the filament is given by Richardson's equation, which is

$$i_s = a' T^{\frac{1}{2}} \epsilon^{-\frac{\phi}{kT}} \qquad (3\text{–}1)$$

* It is customary in electrical discussions to speak of the flow of current as from positive to negative outside the battery or generator. However, in the work on thermionics presented here, the direction of flow will be that of the moving electrons, which is from negative to positive.

where $a'$ and $\phi$ are constants for a given filament, $k$ is Boltzman's constant,* $T$ is the absolute temperature of the filament and $\epsilon = 2.718$, the base of the Naperian logarithms. This equation has been tested and found to hold with great accuracy for pure metals, hot oxides and carbon filaments.

In the derivation of this equation, Richardson compares the emission of electrons with the evaporation of a liquid. That there are numerous electrons moving at random between the neutral atoms of a solid accounts for various optical effects and for the conductivity of a metal for heat and electricity. In a metal which is carrying a current, the electrons are drifting in a definite direction due to the potential difference between its ends. These electrons are comparable to the moving particles of a liquid. Being widely separated, they may be treated as a perfect gas. At any one temperature, their velocities range around a mean value given by Maxwell's distribution law. At room temperature, even the faster electrons cannot escape from the surface because of the opposite charge which they induce on it as they attempt to leave. To escape, their kinetic energy, and hence their velocity, must be sufficiently great to overcome this attraction. On heating the metal, the average velocity of the electrons is increased and some of the faster ones escape from the surface. The hotter the metal, the greater the number escaping, and hence the greater the current, since this equals the number leaving each second times the charge on each. Applying kinetic theory laws, it is possible to compute the number escaping each second and hence obtain equation 3–1. In this derivation, the number of free electrons per cubic centimeter inside the metal is assumed to be independent of the temperature. If this number does vary as the three-halves power of the absolute temperature, then Richardson's equation has the form,

$$i_s = aT^2\epsilon^{-\frac{\phi}{kT}} \qquad (3\text{–}2)$$

* $k$ is equal to two-thirds of the change of the average kinetic energy of translation of a molecule per degree change of temperature and is equal to

$$\frac{R}{N} = \frac{8.315 \times 10^7}{6.064 \times 10^{23}} = 1.372 \times 10^{-16}$$

where $R$ is the universal gas constant and $N$ is Avogadro's number.

It makes very little difference which form is used since variations of $T$ in the exponent of $\epsilon$ cause by far the major variations in the saturation current $i_s$. In fact, the effect of $\sqrt{T}$ or $T^2$ is so small that it has not yet been possible to determine experimentally which is correct.

The accuracy with which Richardson's equation fits the experimental values justifies the assumptions used in its derivation.

**Testing Richardson's Equation.**

By taking logarithms of both sides of equation 3–2 we get

$$\log_\epsilon i_s = \log_\epsilon a + 2 \log_\epsilon T - \frac{\phi}{kT}$$

Changing to natural logarithms and rearranging gives

$$\log_{10} i_s - 2 \log_{10} T = \log_{10} a - \frac{.4343\phi}{k} \frac{1}{T} \qquad (3\text{–}3)$$

$i_s$ may be measured with a milliammeter and $T$ with an optical pyrometer. The left hand side of equation 3–3 is plotted on the vertical while $1/T$ is plotted on the horizontal, as in figure 3–2. If Richardson's equation is correct, this will be a straight line corresponding to the linear equation $y = b - mx$, where $b$ is the $y$-intercept and $m$ is the slope of the line. The occurrence of a term involving the temperature, i.e., of 2 $log_{10}T$, on the left hand side of the equation plays but a small part compared to $log_{10}\, i_s$ and may be regarded as a constant.

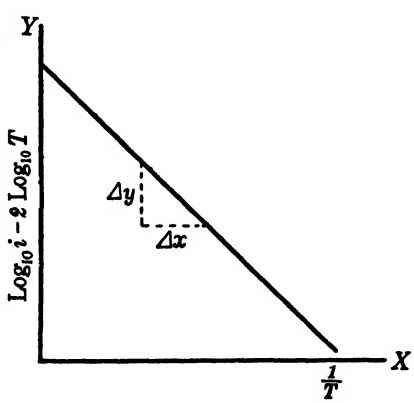


FIG. 3–2. Testing Richardson's equation.

**The Work Function.**

In the derivation of equation 3–1 or 3–2, $\phi$ represents the work in ergs needed to remove one electron from the metal. It is called the *evaporation constant* and is obtained from the slope ($m$) of the line in figure 3–2. Thus

$$\text{Slope } m = \frac{\Delta y}{\Delta x} = \frac{.4343\phi}{k}$$

$$\phi = \frac{1.372 \times 10^{-16}}{.4343} \cdot m \text{ ergs} \qquad (3\text{–}4)$$

This is an important constant of the emitting surface. There will be a more copious emission of electrons from one with a small $\phi$ than from one with a large $\phi$, other conditions being the same. It may be expressed in various other ways such as ergs of work to take unit charge through the surface, volts to remove one electron, or as volts to remove unit charge. The last is the form ordinarily used and is called the electron affinity or *work function* $w$. Now $w/300$ gives e.s.u. or ergs to remove unit charge and $we/300$ gives ergs to remove an electron, which is the evaporation constant. In this, $e$ is the charge on the electron in e.s.u. From this

$$w = \frac{300\phi}{e} \text{ volts} \qquad (3\text{–}5)$$

The work function has been determined for many filaments and is from 3 to 5 volts for metals such as tungsten. (See table 3.) Its value is very low for platinum coated with the oxides of the alkali earths (such as barium and strontium). Such filaments, known as Wehnelt cathodes, give a large electron current even when operated at low temperatures. This "dull emission" insures longer life for the filament and cheaper operation. The work function is also very low for tungsten impregnated with thorium. To "activate" this latter type of filament, a coating of thorium is driven to the surface of the tungsten by heating it at normal temperature, or slightly higher, for several hours. During this time the plate is kept at zero voltage. The work function depends on the smoothness of the surface as well as on the material of which the filament is made.

**Saturation Currents and Space Charges.**

Richardson's equation gives the current flow from a hot cathode to a cold anode when the potentials used are high enough to draw all electrons emitted by the filament over to the plate. This relation is shown by the heavy line $OA$ in figure 3–3 where the current increases exponentially with increasing electron emission as the temperature of the filament is raised. If the voltage on the plate is not sufficiently great, say it is of amount $V_1$, the current does not

rise above a fixed value but follows such a curve as $OV_1$. This is due to the repellent action of the electrons in the region between filament and plate on the outcoming electrons. Although the electrons are moving very rapidly, they may be considered at a given instant as a small cloud or "space charge." This is analogous to the vapor accumulating above a liquid in an enclosed vessel. If a higher voltage is used, say $V_2$, saturation does not start so soon, i.e., the space charge effect begins at a higher temperature $T_2$ instead of $T_1$.

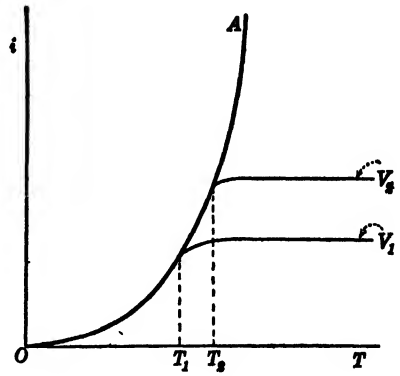


FIG. 3–3. Plate current vs. filament temperature.

The phenomena due to space charge may be shown in another fashion. It has been pointed out that the thermionic current is dependent on both the temperature of the filament and the potential of the plate. Let the temperature be held constant and the voltage varied. The relation then found between the current and voltage is not linear, as in the case of Ohm's law for metallic conduction, since the current increases more rapidly than the first power of the voltage. Child and Langmuir have deduced from theoretical considerations that the voltage must be raised to the three-halves power. Thus

$$i = CV^{\frac{3}{2}} \qquad (3\text{–}6)$$

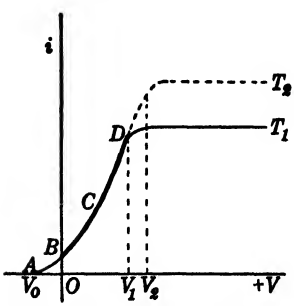


FIG. 3–4. Plate current vs. plate voltage.

where $C$ is a constant. This law assumes that the filament is at such a high temperature that not all the electrons emitted are drawn over to the plate, i.e., a space charge exists. Experimentally, the curves of figure 3–4 are obtained. It is to be noted that a small current passes to the plate when it is slightly negative. This is due to the fact that the electrons have a small initial velocity when leaving the filament sufficient to carry them to the plate against a few volts retarding potential. The

shape of the curve $AB$ may be deduced from Maxwell's distribution law. It will appear as a straight line if logarithms of the current are plotted against voltages.

The second part of the curve, from $B$ to $C$, is given by the three-halves power law where a space charge limits the current. Taking logarithms of both sides of the equation for this portion, we have

$$\log i = \log C + \frac{3}{2} \log V \tag{3–7}$$

the logarithms being to the Naperian base $\epsilon$ or to the base 10 qn both sides. This equation represents a straight line where values of $\log i$ are the ordinates; $\log V$, the abscissæ; $\log C$, the $y$-intercept and $\frac{3}{2}$, the slope as shown in figure 3–5.* Since there is a potential drop down the filament, the voltage $V$ is to be taken as that of the plate battery plus or minus half this drop.

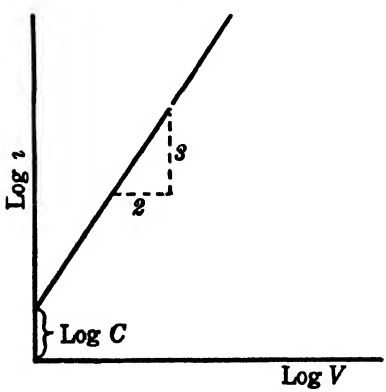


FIG. 3–5. Testing the "three-halves power" law.

The saturation curve from $D$ to $T_1$ (figure 3–4) shows that all electrons emitted at the temperature $T_1$ (absolute) are drawn over to the filament. The relation between this constant current and the temperature is that of Richardson. If the temperature of the filament is raised to $T_2$, saturation does not set in so soon, requiring the higher voltage $V_2$.

To sum up, the current-voltage relation of a two-electrode tube is a combination of three distinct phenomena. First, the current due to initial velocities, which is usually small; second, the current which is limited by space charges and follows the $\frac{3}{2}$ power law, and finally, the saturation effect where all emitted electrons pass to the plate, as given by Richardson's equation.

* If the effect of initial velocities is large, as in the case of low temperatures (the current becomes constant at low voltages), it may be corrected for by the introduction of the voltage $V_0$ into equation 3–6, giving

$$i = C(V + V_0)^{\frac{3}{2}} \tag{3–8}$$

Plotting $i$ against $(V + V_0)^{\frac{3}{2}}$ will give a straight line.

**Photo-electric Phenomena.**

It has also been observed that when light falls on the surface of certain metals, electrons are given off. This is called the *photo-electric* or Hallwachs' effect after an early investigator of the phenomenon. Thus, if ultra-violet light falls on a freshly polished zinc plate, *A* of figure 3–6, electrons are emitted and may be observed by the deflection of an electrometer. There are two relationships between the ejected electrons and the incident light rays. First, if the intensity of the light is increased, the number of electrons, i.e., the photo-electric current, increases. Doubling the intensity of the light doubles the photo-electric current, etc. This linear relation is exact over as wide a range as from 0.1 to 1000 foot-candles. Hence, the photo-electric currents may be used over wide limits to measure the intensity of a beam of light. It is important that the wave-length or wave-lengths involved in the light remain unchanged in such measurements.

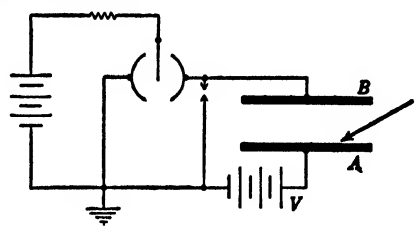


FIG. 3–6. Connections for studying the photo-electric effect.

The second relationship between the photo-electrons and the incident light involves the energy (or velocity) of the electrons and the frequency (or wave-length) of the light. In figure 3–6, electrons ejected from the plate *A* by the light are drawn back to *A* by connecting the battery *V* with the proper polarity. With *V* such that the upper plate *B* (of the same material as *A*) is only slightly negative, the electrometer will indicate a flow of electrons from *A* to *B*. As *V* is made more and more negative, the current decreases and will cease to flow at a clearly defined negative potential $V_0$. Thus $V_0 e$ is the energy needed to repel the fastest electrons of charge *e*. Then

$$V_0 e = \frac{1}{2} m v^2 \qquad (3\text{–}9)$$

where *v* is the maximum velocity of the electrons and *m* is the mass of one electron. $V_0$ and *e* are to be expressed in the same units (e.m.u. or e.s.u.) if the energy is to be in ergs.

The maximum velocity (or energy) of the ejected electrons does not depend on the intensity of the incident light but does depend on its frequency $\nu$ in a linear fashion as may be seen in figure 3–7.

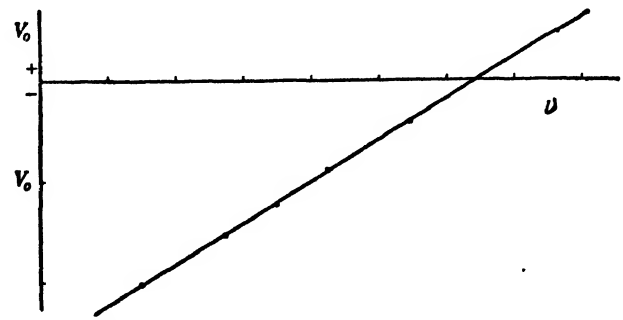


FIG. 3–7. Maximum velocity of photo-electrons vs. frequency of the incident light.

For any frequency $\nu$ of the incident light, Einstein has given the equation

$$h\nu = V_0 e + \phi \qquad (3\text{–}10)$$

in which $h$ is Planck's constant, $6.55 \times 10^{-27}$, and $\phi$ is the energy needed to remove an electron from the metal.* Thus $h\nu$, the part of the energy of the incident light which is transferred to each electron, is sufficient to free the electron from the metal and give it a kinetic energy equal to $V_0 e$.

This phenomenon is one which is very difficult to interpret on any atomic picture coupled with the wave theory of light. No mechanical analogy exists which will account for the energy acquired by the electron and the frequency of the incident light. If the energy is considered as concentrated in bundles of amount $h\nu$ (light quantum theory) we may imagine this energy going over completely to the ejection of an electron.

A particular frequency $\nu_0$ may be found for which the energy of the incident light is just insufficient to remove an electron. The wave-length $\lambda_0$ corresponding to this frequency ($\lambda_0 = c/\nu_0$

* If the plates $A$ and $B$ are not made of the same material, an allowance must be made for their contact potential difference in the voltmeter reading to obtain the correct value of $V_0$.

where $c$ is the velocity of light) is called the *photo-electric long wave-length limit.* (See table 3.)

If the frequency of the incident radiation is very great as in the case of X-rays, the energy needed for the removal of an electron from the metal ($\phi$) becomes negligible in comparison to the kinetic energy ($V_0 e$) so that

$$V_0 e = h\nu \tag{3-11}$$

It is found that the more highly electropositive metals such as sodium and potassium give a more copious emission of photo-electrons than do other metals under the same conditions. Further, the long wave-length limits for sodium and potassium lie in the red part of the visible spectrum whereas for other metals, such as magnesium, zinc, aluminum, etc., electrons are ejected only by light of wave-length smaller than 4500 to 2500 angstroms, i.e., by radiations in the ultra-violet. Gases and certain non-metals such as carbon show a photo-electric effect but this is much smaller than for metals and necessitates the use of a much shorter wave-length radiation before setting in. Those substances which show phosphorescence (not fluorescence) are photo-electric. It has also been observed that adsorbed films of gas on the emitting surface cause erratic emission and a fatiguing effect with long exposure. When this is eliminated by preparing a gas-free surface in a vacuum, extremely feeble sources of light may be accurately measured immediately after prolonged exposure to such intense sources as direct sunlight (10,000 foot candles). Photo-electric cells are prepared by depositing a suitable metal, such as potassium hydride or sodium, on the inner surface of an evacuated glass bulb, a small area being left clear to admit the light. The sensitive surface is the negative terminal as indicated in figure 3–8. The positive terminal consists of a wire supported in the middle of the bulb. In one type of cell, sodium is introduced into the bulb by a process of electrolysis through the glass walls after complete evacuation and sealing off. In another type, a small amount of inert gas, such as helium, argon or neon, is introduced in order to magnify the photo-electric current by the ionization of the gas. The photo-electric currents may also be

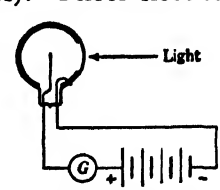


FIG. 3–8. Study of a photo-electric cell.

amplified by auxiliary vacuum tubes as used in radio. Such a circuit is shown in figure 3–9. In any of these cells the current flow

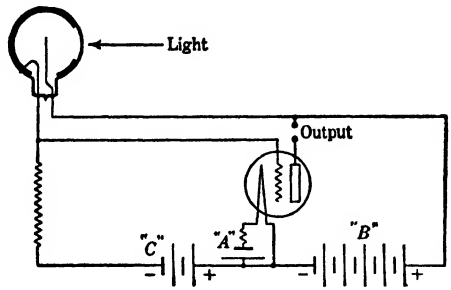


FIG. 3–9. Connections for amplifying photoelectric currents.

starts the instant light falls on the surface. Variations in light intensity occurring in $10^{-8}$ of a second or more may be recorded. This is made use of in television, i.e., the transmission of moving pictures.

## EXPERIMENT 3–1. THERMIONICS

### A STUDY OF THE TWO-ELECTRODE VACUUM TUBE

The purpose of this experiment is to check the validity of the space charge equation and of Richardson's equation, and to compute the work function of the filament used.

1. Connect the apparatus as in figure 3–1. The tube may be any of the three-electrode radio tubes if the grid and plate are connected together.

2. Keeping the filament at constant temperature, record the current $i$ with a 0–10–100 milliammeter as the plate voltage $V$ is varied say from 0 to 200 volts. Repeat using several filament temperatures and plot as in figure 3–4.

3. Plot log $i$ against log $V$ as in figure 3–5 and determine the slope of the straight section corresponding to the part of curve $BC$, figure 3–4. (Use plate voltages corrected for the drop of potential along the filament.)

4. To test Richardson's equation, apply a voltage in excess of $V_2$, figure 3–4 and measure the current at various filament tempera-

tures. These temperatures may be measured with an optical pyrometer. This consists of a calibrated lamp in the eyepiece of a telescope and is adjusted so that the standard filament and that of the two-electrode tube are in focus at the same time. The current through the standard is varied until the two intensities are the same, and its value recorded. The calibration chart gives the temperature in terms of this current.* Since it is true that the filament is always cooler near the supports, the calibration is usually made at the center of the wire. This same point must be used in determining an unknown temperature. For measuring the higher temperatures, a more accurate comparison is possible if a green or a red glass is used over the eyepiece of the pyrometer, provided, of course, that the calibration has been made under these conditions. For very high temperatures, a rotating sector may be used in front of the pyrometer. A calibration chart, made with this in operation, does not depend appreciably on the speed of the shutter provided it exceeds some sixteen times a second. It does depend on the relative areas of the shutter and open space. If the glass walls of the two-electrode tube are darkened by some deposit, correct values for the temperature of the filament will not be obtained but the test of Richardson's equation (see figure 3–2) is not invalidated.

5. Plot the curve $OA$, figure 3–3, and test Richardson's equation as in figure 3–2.

6. Compute the work function of the filament using equations 3–4 and 3–5.

## EXPERIMENT 3–2

### A STUDY OF A PHOTO-ELECTRIC CELL

Connect a photo-electric cell as in figure 3–8 using voltages from 0 to 200. The light may be a 40–100 watt frosted Mazda.

Leaving the lamp at a fixed distance from the cell, vary the voltage and plot a curve of galvanometer deflections as ordinates and voltages as abscissæ. Repeat with the lamp at various measured distances and plot on the same graph.

* This calibration was determined by matching the filament intensity with that of various metals raised to melting point in a vacuum. The melting points of different substances will be found in published tables of physical constants.

Next a curve is to be plotted showing the galvanometer deflections or photo-electric currents as the intensity of illumination is varied. If the current and voltage of the lamp remain constant the intensity is inversely proportional to the square of the distance $d$ between the lamp and the cell (center to center). A plot of galvanometer deflections as ordinates and $1/d^2$ as abscissæ should give a straight line.

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# CHAPTER 4

## ELECTRON PHENOMENA

**Cathode Rays.**

Connect the secondary of an induction coil to two metal electrodes sealed in a glass tube, as in figure 4–1, and study the passage of electricity between them as the air is gradually removed. A point will be reached, at pressures around 0.05–0.005 mm. of mercury, where a greenish or bluish fluorescence appears on the walls of the tube and a faint streak of light may be seen coming from the negative electrode. Many interesting phenomena may now be observed. For example, a solid object at $X$ casts a shadow on the walls at $B$. Since the edges of this shadow are clean cut, the rays which cause the glass to fluoresce must have travelled in straight lines from the cathode. If a concave cathode is used, the rays come to a focus, where they may melt a piece of metal foil. This shows that they leave the cathode perpendicularly and possess great energy. If they strike a light, carefully pivoted paddle wheel, they cause it to rotate, showing that they have inertia or mass.* Then it must be true that they have either great mass or high velocity.

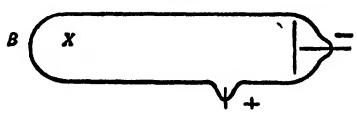

FIG. 4–1. To study cathode rays.

These "cathode rays" can be deflected by an electric or magnetic field. Hence, they consist of electrical charges in motion. From the direction in which the rays are deflected, their charge is found to be negative. This has been verified by catching them inside a small metal cup (a Faraday chamber) which is connected to an electrometer.

If a thin aluminum window is used instead of the glass at B, figure 4–1, cathode rays will be found to emerge into the air. These

* This experiment is usually performed in a tube containing a moderate amount of gas. The paddle wheel is then set into rotation by the heat caused by the bombarding rays, as in Crookes' radiometer, and the effect discussed is masked. A high degree of evacuation should be used.

will travel for a distance of several centimeters. They are then called Lenard rays, after their discoverer, and are produced in large quantities by the Coolidge cathode-ray tubes.

The motion of cathode rays may be studied by the fluorescence they produce when they strike glass or a luminescent screen such as calcium tungstate, by the streak of light which they produce in a gas through which they are passing, by metal collectors leading to an electrometer, and by the blackening which they can produce on a photographic plate.

Electrons emitted from a hot filament in a vacuum exhibit these same properties. This indicates that cathode rays consist of electrons. They can be produced in a vacuum tube regardless of the gas used or the cathode material, so that they are a common constituent of all matter. It is also interesting to note that, since they can pass through thin aluminum foil, they must be comparatively small and the inter-atomic spaces of matter must be comparatively large.

When cathode rays are suddenly stopped by a solid body, they set up X-rays much as the bullets of a machine gun striking a target produce sound waves.

As the following experiments will show, the velocity of these electrons is great and their mass is very small.

**The Ratio of Charge to Mass and the Velocity of Cathode Rays.** J. J. Thomson (1897) measured the ratio of charge to mass ($e/m$) and the velocity ($v$) of cathode rays by bending them in a combined electric and magnetic field. A filament * $F$, in figure 4–2, is sealed in a vacuum tube at a pressure of about 0.01 mm. of mercury. It emits electrons, each of which has a mass of $m$ grams and carries a charge of $e$ electromagnetic units. These are accelerated to an anode $A$ by the potential $V$ (e.m.u.) and pass through a small hole with a velocity of $v$ centimeters per second. Ordinarily they pass straight ahead to form a point of light on the screen at $S$. This screen consists of a glass plate coated with a fluorescent material, such as luminescent calcium tungstate or zinc sulphide. If a uniform magnetic field of strength $H$ gausses is applied perpendicularly across the condenser $BC$, as indicated by the dots, the

* J. J. Thomson used a cold electrode but the experiment is here described using a hot filament.

spot of light is deflected to $S'$, since the rays are bent into a circular path of radius $r$ centimeters while moving through the field $BC$.

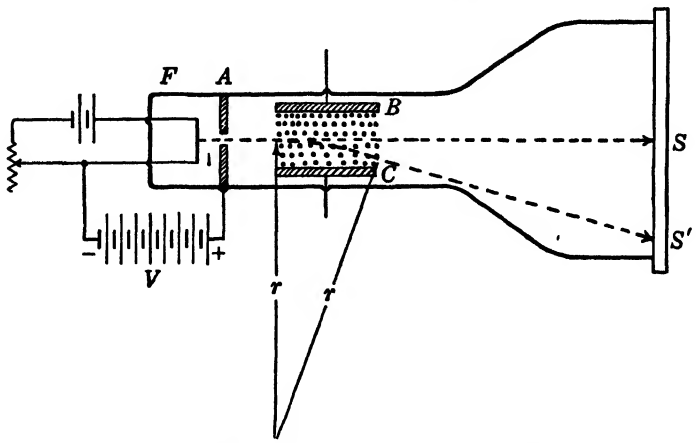


FIG. 4–2. Measurement of $e/m$ and $v$ of cathode rays.

Now, by definition of the electromagnetic unit of current, the force on one centimeter of current is $Hi$, where $i$ is the current. If $n$ be the number of electrons per cubic centimeter, then $i = nev$, and the force causing the deflection is $Hnev$. The force on each electron is then $Hev$ and is equal to the centrifugal force $mv^2/r$ acting on each electron. Then

$$Hev = mv^2/r, \quad \text{or} \quad e/m = v/Hr \tag{4–1}$$

If one of the quantities, $v$ or $e/m$, can be determined, the other can be found, since $H$ and $r$ are measurable quantities. The bending due to the magnetic field can be counterbalanced so that the spot of light returns to $S$ by applying an electric force equal to the magnetic force at each point between the metal plates. The electrical force on each electron is the $Fe$, where $F$ is the electrical field strength measured in electromagnetic units. When the spot of light has been returned to $S$,

$$Fe = Hev, \quad \text{or} \quad v = F/H \tag{4–2}$$

so that

$$e/m = F/H^2r \tag{4–3}$$

A second method may be used for determining the ratio of charge to mass and the velocity of the electrons, in which the

curvature produced by a magnetic field is observed. The work done on the electrons between their source (the filament) and the anode is $Ve$, by definition of the potential $V$. This assumes that every point on the filament is at the same potential and that the electrons have zero velocity as they leave the filament. Corrections for departures from the ideal conditions assumed need not be made except for precise work or when the accelerating potential $V$ is comparatively small. As the electrons pass through the hole in the anode, they have a velocity $v$ and hence a kinetic energy equal to $mv^2/2$ so that

$$Ve = mv^2/2 \tag{4–4}$$

Dividing this equation by the equation $Hev = mv^2/r$ gives

$$e/m = 2V/H^2r^2 \tag{4–5}$$

In a third method, due to Busch,* a rotating magnetic field is placed around a discharge tube so that the electrons emerge in a hollow, cone-shaped bundle from a small hole in the anode. They strike a luminescent screen some distance away and produce a ring of light. By means of a solenoid, a magnetic field is produced, whose lines of force are parallel to a line joining the hole in the anode and the center of the screen. Since the electrons have a velocity component perpendicular to this field, they are deflected at right angles. The resulting motion is a spiral down the tube. When the magnetic field strength, the velocity of the electrons and the distance between the anode and screen have been properly adjusted, all the electrons rotate once about the axis of the tube during the time they are passing from anode to screen. The result is that they all come to a common focal point at the center of the screen. Under these conditions, it is possible to compute the value of $e/m$ in the following manner.

Let $t$ be the time for one rotation, which is also equal to the time for the linear transit from anode to screen, and let $v$ be the velocity of the electrons. Then $v \sin\theta$, where $\theta$ is the angle between the emerging electrons and the axis, will be the component of velocity perpendicular to the magnetic field. As a result of this motion, the electrons will be bent into a circle of radius $r$. Equating the

* For a modification of this method and a diagram of the apparatus, see Experiment 4–2 at the end of this chapter.

magnetic and centrifugal forces, $m(v \sin\theta)^2/r = He(v \sin\theta)$, giving $m\omega = He$ where $\omega = v \sin\theta/r$, the angular velocity of the electrons, which is equal to $2\pi/t$. Hence

$$t = \frac{2\pi}{He/m} \tag{4–6}$$

If, now, $l$ be the distance between the anode and the screen,

$$l = (v \cos\theta)t \tag{4–7}$$

where $v \cos\theta$ is the uniform velocity of the electrons along the axis of the tube. Since the $t$'s are the same when the electrons have been brought to a focus, we have

$$l = \frac{2\pi v \cos\theta}{He/m} \tag{4–8}$$

From equation 4–4, we may determine the velocity of the electrons as $v = \sqrt{2Ve/m}$, giving

$$l = \frac{2\pi\sqrt{2Ve/m}\cos\theta}{He/m} \tag{4–9}$$

Solving this equation,

$$\frac{e}{m} = \frac{8\pi^2 V \cos\theta}{H^2 l^2} \tag{4–10}$$

The velocity $v$ of the cathode rays is large, ranging from two thousandths to ninety-seven hundredths of the velocity of light, i.e., from 370 to 180,000 miles per second, according to the accelerating potential applied. The value of the ratio of charge to mass,

$$e/m = 1.769 \times 10^7 \text{ e.m.u. per gram,}$$

is independent of the method used to produce the electrons.

**The Mass of the Electron.**

From the shot effect, previously discussed in Chapter 2, the charge on the electrons emitted by a hot filament is $4.77 \times 10^{-10}$ e.s.u. Substituting this in the value of $e/m$ just found, gives the mass of the electron as

$$m = 8.99 \times 10^{-28} \text{ grams,}$$

which is 1/1849 that of the hydrogen atom.

With refined technique, various experimenters have found that $e/m$ decreases as the velocity increases. Thus

$$\frac{m_1 \text{ (accelerating potential = 4000 volts)}}{m_2 \text{ (accelerating potential = 1000 volts)}} = 1.007$$

With fast beta rays, the ratio may become as great as three or four to one. There is no evidence that the charge varies in the least, hence the mass must be greater for the higher velocities. An equation, first used by Lorentz and later included in the *special theory of relativity*, expresses this variation of mass with velocity. It is

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} \qquad (4\text{–}11)$$

where $m$ is the mass of the particle travelling with velocity $v$, $m_0$ is the rest mass, or mass at zero velocity and $c$ is the velocity of light ($3 \times 10^{10}$ cm./sec.) Using this equation, the computed masses for electrons accelerated with 4000 and 1000 volts have the ratio 1.006, in essential agreement with the experimental value.

**The Wave-length of an Electron.**

By assuming that the positively charged part of an atom was concentrated into a compact nucleus, Rutherford, in his classic treatment, was able to deduce an equation which accurately predicted the scattering of the comparatively heavy, slow moving, positively charged particles sent out by certain radioactive substances. These alpha particles possess such great kinetic energy that they can penetrate the surrounding swarm of electrons in an atom and approach very close to the nucleus. The same is true for the very fast beta particles emitted by certain radioactive substances. These, although possessing but little mass, have velocities large enough to cause them to penetrate the exterior parts of atoms. But when experiments were tried with slower electrons, such as those from hot filaments in a vacuum tube, no accurate prediction could be made as to their distribution after impinging on solid substances. Apparently their passage was markedly influenced by the outer parts of the atoms. Attempts to deduce the arrangement of the exterior electrons of an atom using the corpuscular or ray-like picture were not very successful. In 1927 Da-

visson and Germer used the apparatus shown in figure 4–3 to study the scattering of medium velocity electrons. The entire apparatus is enclosed in a chamber which is carefully evacuated, even to baking out the gases adsorbed in the metal parts. Electrons produced by the hot filament $F$ are given an acceleration by the enclosing positively charged chamber $C$ and pass through the collimating slits $SS$ to strike the target $T$, a single crystal of nickel, from which they are scattered in various directions. The shielded collecting chamber $A$ is connected to a galvanometer and may be moved around the arc of a circle centering at $T$. In this way the distribution of the electrons at various angles $\theta$ can be determined.

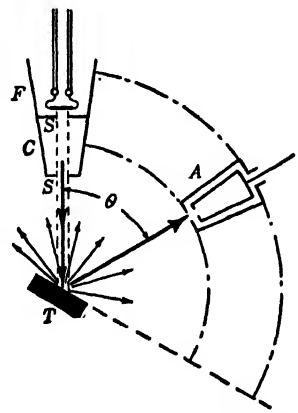


FIG. 4–3. The Davisson-Germer experiment.

A retarding potential is applied between the shield of the collecting chamber $A$ and the target $T$ so that only those secondary or scattered electrons with velocities nearly equal to that of the incident electrons can reach the chamber itself. Under these conditions, peculiar distributions of the electrons are found. First of all there are regular reflections, where the angle of reflection equals the angle of incidence. This is a surprising fact since the electrons are small compared to the atoms. One would hardly expect such deflections of the lead shot fired from a gun at a pile of cannon balls, each of which consists of a miniature planetary system of shot revolving around a central nucleus, with all parts electrically charged. But the reflection of X-rays from a single crystal does follow such a law, as proved in the usual Bragg spectra and illustrated in figure 4–4. Thus, there is a fundamental analogy between X-rays and electrons.

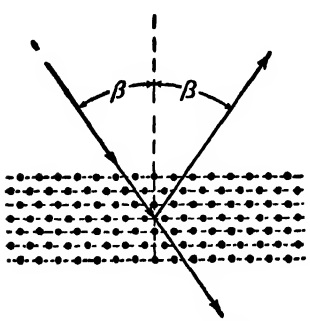


FIG. 4–4. Reflection of X-rays.

If the analogy between X-rays and electrons is true, then there

must be a selective reflection of the electrons just as certain X-ray wave-lengths are reflected from a given crystal in a fixed position while others are not reflected. Figure 4–5 shows the intensity of

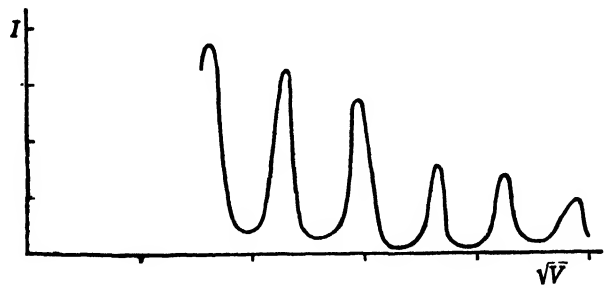


FIG. 4–5. Selective reflection of electrons of different velocities.

those electrons reflected with the angle of reflection equal to the angle of incidence, plotted against the square root of the accelerating potential. This suggests that a wave-length be associated with the electron, whose value is proportional to the square root of the accelerating potential, i.e., to the velocity of the electron. Using the same formula used by Bragg in determining the wave-length of X-rays and using the usual space lattice $d$ for the nickel crystal, a wave-length for the electrons may be deduced.

From a theory of de Broglie, the wave-length $\lambda$ of an electron should be given by

$$\lambda = \frac{h}{mv} \tag{4–12}$$

where $h$ is Planck's constant ($6.55 \times 10^{-27}$), $m$ is the mass and $v$ the velocity of the electron. The wave-lengths obtained by the method outlined in the preceding paragraph agree with this for the faster electrons but not for the slower ones. The lack of agreement is due to a bending of the electron beam by refraction, which is to say that the index of refraction of nickel for electrons is not unity. Calculations show that it ranges from 1.0 to 1.2, rising at the longer wave-lengths and showing a marked discontinuity at $\lambda = 1.3$ angstroms (for nickel), which is suggestive of anomalous dispersion.

The Laue or diffraction phenomena observed with X-rays reflected from the various space lattice planes of a single crystal

can be observed with electrons, again allowing a simple interpretation if the electrons be considered as having wave-lengths dependent on their velocities as in the equation above. Using fast cathode rays, G. P. Thomson has succeeded in obtaining diffraction patterns (rings) from electrons which have passed through extremely thin foils of such substances as gold, aluminum, collodion, platinum, etc. The arrangement of his apparatus is shown in figure 4–6. A

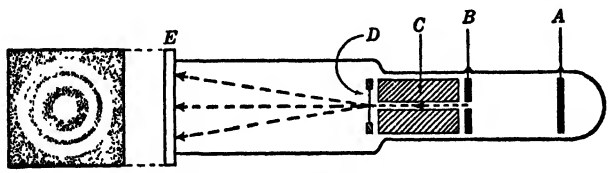


FIG. 4–6. Electron diffraction apparatus.

high potential (10,000–60,000 volts) is applied to the electrodes *A* and *B*. Electrons are accelerated through the small hole in *B* and collimated by the capillary hole in the metal tube *C*. The thin foil *D* diffracts the electrons to the photographic plate *E* where they appear as rings about a central spot (as in the Debye-Scherrer method of X-ray analysis). A magnetic field between *D* and *E* moves the entire pattern as a unit. From the accelerating potential between *A* and *B* and the diameter of the rings on *E*, he has calculated space lattice distances in the diffracting foils, assuming that the wave-length was that given by the equation $\lambda = h/mv$. He found very good agreement with the values obtained by X-ray analysis for the metal foils used.

**The Absorption of Electrons.**

When the electrons are travelling comparatively slowly, their velocities being less than $3 \times 10^8$ centimeters per second, they are easily absorbed, even by gases. Thus all electrons leaving a source do not travel the same distance. This has been observed by C. Ramsauer, who bent the electrons into a circular path and, by means of a series of chambers, observed the number travelling a known distance in a certain gas. As in other cases of absorption, the number reaching a definite distance is given by an exponential law. Let *dn* be the number of electrons absorbed in passing through

a thickness $dx$ of the gas. This will be proportional to the number present. Hence

$$dn = - Apn\, dx$$

where $p$ is the pressure of the gas in millimeters of mercury, $A$ is the constant of proportionality and the negative sign is used to indicate the decrease in number of electrons as they pass through. Then

$$\frac{dn}{n} = - Ap\, dx$$

$$\log_\epsilon n = - Apx + \text{constant}$$

Now when $x = 0$, $\log_\epsilon n_0 = \text{constant}$, so that

$$\log_\epsilon \frac{n}{n_0} = - Apx$$

$$n = n_0 \epsilon^{-Apx} \tag{4–13}$$

where $n$ is the number travelling the distance $x$, $n_0$ the number which started, and $\epsilon$ the base of the Naperian system of logarithms. The constant $A$ can be interpreted as the product of the number of atoms $Q$ in one cubic centimeter of the gas (at its existing pressure and temperature) and the "intercepting cross-section" $\sigma$ of each atom to an electron, i.e.,

$$\sigma Q = A \tag{4–14}$$

If the atoms are considered as spheres, then

$$\pi r^2 = \sigma,$$

from which

$$r = \sqrt{A/\pi Q} \tag{4–15}$$

The interesting point is this, that the effective cross-section of an atom, while independent of the velocity of the electron in many cases, does change in some cases. With argon, for example, its value at small velocities is extremely low; it then rises to a maximum around $2.4 \times 10^8$ centimeters per second (10 volts) and then decreases for still higher velocities, approaching values given for the cross-section by measurements on the viscosity of gases.

## EXPERIMENT 4–1

### THE RATIO OF CHARGE TO MASS AND THE VELOCITY OF CATHODE RAYS

*Apparatus.* — In figure 4–7, the electrons are produced by the filament *F*. This may be heated by means of a storage battery or

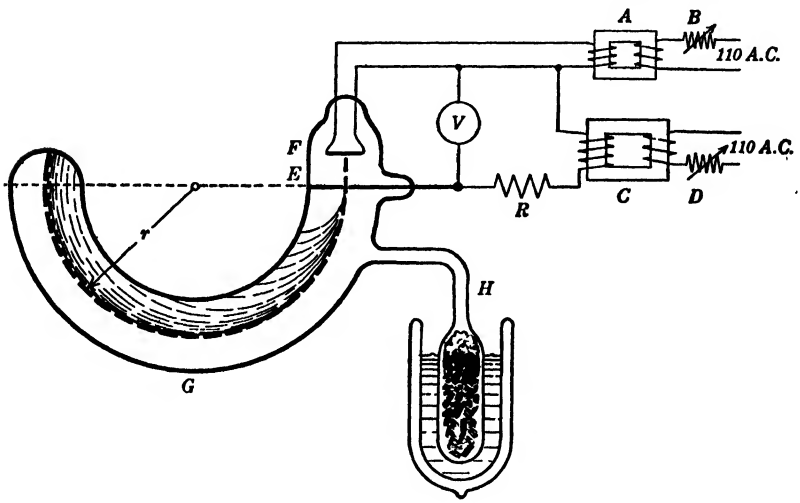


FIG. 4-7. Apparatus for determining $e/m$ and $v$.

by the use of a step-down transformer. (Bell-ringing or toy transformers have been used satisfactorily.) The control rheostat *B* is preferably located in the primary circuit since the secondary is connected to the high voltage used to accelerate the electrons. The accelerating potential is supplied by the step-up transformer *C*, whose secondary voltage may be varied from 200 to 600 volts by means of the rheostat *D*. This potential is measured by the high resistance A.C. voltmeter *V* (say of the Kelvin electrostatic type). To prevent excessive current flow between the filament *F* and the anode *E*, with consequent destruction of the filament, the resistance *R* is placed in the circuit as shown. This may consist of half a dozen electric light bulbs connected in series.

The vacuum tube *G* may be a glass tube, about 3 cm. in diameter, bent into a circle of radius 6 cm. A ground joint sealed with wax may be used for the filament to allow replacements. This joint

should be about 10 cm. from the filament to avoid melting its wax by the heat from the filament. The filament should be of the dull emitter type (see the reference to Arnold's paper at the end of Chapter 3 for its preparation), otherwise the light from the electron beam will be masked by the light from the filament. The slit in the anode may be about 1 mm. wide and 5 mm. long, placed vertically to the plane of the paper in figure 4–7. The tube is exhausted to about 0.005 mm. pressure or until the electron beam is clearly defined as it passes through the anode. If the pressure is too high, the beam will be diffuse and accurate measurements can not be made. If the pressure is too low, the beam will not be visible.* By the use of a charcoal trap *H* which has been baked out during the evacuation, and liquid air, the pressure may be adjusted quite satisfactorily.

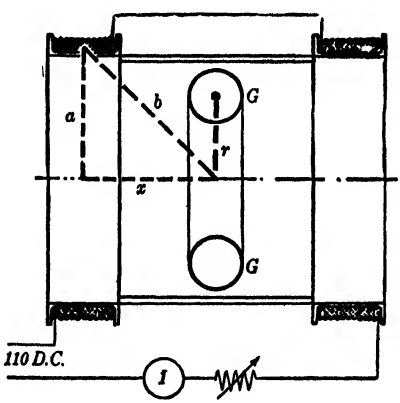


FIG. 4–8. The field coils.

The electron beam is bent into a circular path by means of a magnetic field whose lines of force are perpendicular to the plane of the paper (Fig. 4–7). This field may be produced by the double coil shown in figure 4–8. This is constructed after the fashion of the Helmholtz-Gaugain galvanometer coils so as to insure uniform field strength over the region where the vacuum tube *G* is located. Each coil may be about 13 cm. in diameter, 2.5 cm. wide, of 60 turns of No. 16 D.C.C. copper wire. For simplicity of calculation of the field strength, the distance between the centers of the coils should equal their radius, i.e., $2x = a$. They are connected in series aiding. The current (1 to 5

* Good results may be obtained by exhausting the tube as highly as possible and observing the path of the electrons by a series of wire gauzes coated with luminescent material. The luminescent material is sprinkled onto a thin layer of water glass on the gauze. (Be sure to leave the holes clear). The series of gauzes, each of which is perpendicular to the electron beam, is supported by a small metal band fastened at its end to the anode. This also serves to prevent the accumulation of electrical charges on the walls of the glass tube.

amperes) is controlled by a rheostat and measured with the ammeter $I$.

Since the accelerating potential is alternating, electrons pass through the anode only half the time, i.e., when it is positive. They emerge with all velocities from zero to a maximum obtained under the maximum voltage $V$. Those with greatest velocity will be bent the least and vice versa, as indicated by the dotted curves in figure 4–7. The outer edge of this beam will be found to be clearly defined and should be used in measuring the radius $r$. Since this corresponds to electrons of maximum velocity, all voltmeter readings (effective values) should be multiplied by $\sqrt{2}$.

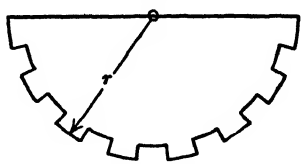


FIG. 4-9. For measurement of the radius of the electron beam.

The accuracy of the experiment is largely determined by the measurement of the radius $r$. A notched cardboard semicircle, figure 4–9, is placed about two centimeters above a similiar semicircle. These are cut to a carefully determined radius and placed over the tube $G$. Two semicircles are used to avoid parallax. The electron beam may be seen between the notches. The accelerating potential and the current through the field coils are varied until the beam just fits the cardboard circles. Its radius is then known.

*Procedure.* — 1. The filament is heated *dull* red. If electrons do not come off immediately it may be necessary to heat the filament to a yellow color for a short time.

2. The accelerating potential $V$ (volts) and the field current $I$ (amperes) are varied until the beam fits the circle of known radius $r$ (cm.)

3. The values of $V$ and $I$ are then recorded.

4. This is repeated from four to nine times with various values of $V$ and $I$.

*Calculations.* — 1. The field strength $H$ is calculated from the equation

$$H = \frac{2\pi n a^2 I}{10 b^3}\left[1 + \frac{3}{4}\frac{r^2}{b^4}\,(a^2 - 4x^2) + \ldots\right] \text{gausses} \quad (4\text{–}16)$$

where $n$ is the total number of turns on both coils, $I$ is the current

in amperes, $a$, $b$, $x$, and $r$ are the distances in centimeters indicated in figure 4–8.

2. The ratio of charge to mass is calculated from the equation

$$\frac{e}{m} = \frac{2\sqrt{2}\ V \times 10^8}{H^2 r^2} \frac{\text{e.m.u.}}{\text{gram}} \tag{4–17}$$

3. The velocity of the electrons is calculated from the equation

$$v = \frac{2\sqrt{2}V \times 10^8}{Hr} \frac{\text{cm.}}{\text{sec.}} \tag{4–18}$$

**EXPERIMENT 4–2**

THE RATIO OF CHARGE TO MASS AND THE VELOCITY OF CATHODE RAYS. MODIFIED BUSCH METHOD.

*Apparatus.* — In figure 4–10, the electrons emitted by the fila-

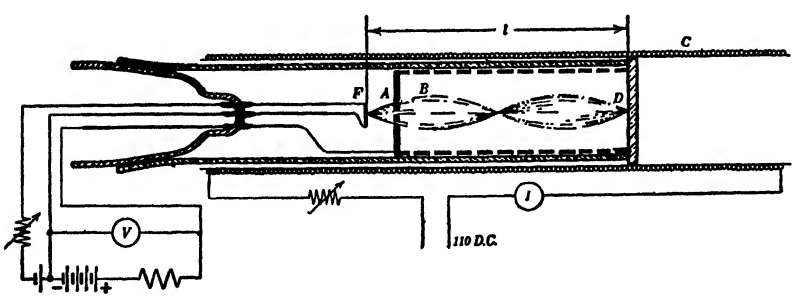


FIG. 4–10. Modified Busch method for determining $e/m$ and $v$.

ment $F$, which is located in a very high vacuum, are accelerated to the anode $A$ by the voltage $V$ and pass through a hole. They emerge into the space $B$ in the form of a cone-shaped bundle and are bent into a spiral by the magnetic field of the solenoid $C$. They come to a focus on the luminescent screen at $D$, producing a point of light when the current $I$ and the voltage $V$ have been properly adjusted.

Details of construction are as follows: The filament is a dull emitter operated by a storage battery or step-down transformer. The accelerating potential is 200 to 600 volts obtained from "$B$" batteries. $V$ is a high resistance D.C. voltmeter. A protective resistance of half a dozen light bulbs is placed in series with the accelerating voltage. Correction for half the voltage drop in the filament must be made to readings of $V$ if direct current is used to heat the filament. The glass tube is 5 cm. in diameter and 30 cm. long. Distance from the ground joint to filament is about 10 cm.; from filament

to anode, 2 mm. to 2 cm.; and from filament to the screen, about 20 cm. The diameter of the hole in the anode is about 2 mm. or, if covered with wire gauze, may be as large as 1 cm.

Fastened to the anode is a tube of non magnetic material (gauze may be used) which extends down the tube $B$ to the screen $D$ and prevents the accumulation of charges on the glass walls. The screen may be prepared as follows. A mixture of luminescent calcium tungstate and zinc sulphide (half and half) in powdered form, is sifted through a fine cloth screen onto a glass plate freshly covered with a thin layer of water glass (sodium silicate). Another method is to place an undeveloped photographic plate directly in hypo for about fifteen minutes. It is then washed in water and placed in the bottom of a shallow dish. Mix the luminescent powder with alcohol, shake thoroughly and pour into the dish. After a few minutes carefully suck out the alcohol with a pipette and allow the screen to dry. For very intense electron beams it is well to sputter a half coat of silver, gold or platinum over the luminescent material. This does not materially affect the luminosity but, when properly grounded, prevents the accumulation of a negative charge on the screen.

The solenoid $C$, carrying from one to four amperes, is 40–50 cm. long and 6–10 cm. in diameter. No. 18 D.C.C. wire may be used for its winding.

The magnetic field strength $H$ of the solenoid may be calculated from the equation

$$H = 4\pi nI/10 \text{ gausses.} \qquad (4\text{–}19)$$

where $n$ is the number of turns of wire per centimeter and $I$ is the current in amperes. Substituting this in equation 4–10 and expressing $V$ in volts, gives

$$\frac{e}{m} = \left(\frac{5 \times 10^9}{n^2 l^2}\right) \frac{V \cos\theta}{I^2} \frac{\text{e.m.u.}}{\text{gram}} \qquad (4\text{–}20)$$

$Cos\theta$ may be obtained by observing the radius of the luminous area on the screen when there is no magnetic field. This distance divided by $l$ gives $tan\theta$. It will usually be found that $cos\theta$ does not differ from unity by more than one per cent, and may be neglected for class room use. The distance $l$ (cm.) is to be measured from the filament and not from the anode since the electrons start spiralling as they leave the filament. Difficulty will be encountered in determining the exact focus because a solid cone of electrons is used instead of a hollow bundle and because of a charge of positive ions which form around the path of the electrons. A wide range of readings around the focussing point should be taken and an average value of $e/m$ determined. If the magnetic field strength be in-

creased beyond the first focal point, the electrons may be caused to make two, three or more complete spirals, each producing a sharp focus. The distance $l$ must then be taken as one-half, one-third, etc., of the value shown in figure 4–10.

*Procedure.* — 1. Heat the filament *dull* red. If electrons do not come off immediately it may be necessary to heat the filament to a yellow color for a short time.

2. Adjust the voltage $V$ and the current $I$ until a sharp point of light is seen on the screen $D$. Record $V$ and $I$ simultaneously.

3. Repeat this for adjustments near this focal point.

4. Repeat (2) and (3) with four or more different combinations of $V$ and $I$.

5. Measure the distance $l$ in cm. and determine the number of turns $n$ of wire per cm. of the solenoid.

*Calculations.* — 1. From equation 4–20, calculate $e/m$, neglecting $\cos\theta$, for all sets of data above. Average and compare with the accepted value.

2. Using equation 4–4, compute several values of the velocity of the electrons for their corresponding accelerating potentials. Compare with values given in the table at the end of the book. Note that the latter include the relativity correction for change of mass with velocity.

## NOTES

Various modifications of the apparatus for determining $e/m$ and $v$ for cathode rays are in use today. A rough description of some of these follows, the details being left to the instructor in charge.

1. A Braun tube may be used in the Busch method, with reasonable accuracy.

2. Classen Method: Electrons from a hot filament are accelerated through a hole in the anode and are deflected by a strong magnetic field into a small circle (2 or 3 cm. radius). They are observed on a luminescent surface lying in the plane of the anode. The field is reversed, deflecting the electrons to the opposite side of the hole, where they are observed on the screen. The distance between the two spots of light is equal to four times the radius of the electron circle. The filament must be very close to the anode.

3. The Thomson method, where the electric and magnetic deflections are equal, may be used with a Braun tube with fair ac-

curacy. The magnetic field coils may be separated to various distances from the tube. The curve of deflections of the electron beam against the distance between the coils can then be extrapolated to obtain the deflection which would have resulted from the homogeneous field produced if the coils were in contact.

4. Magnetron method: See reference to A. W. Hull at the end of this chapter. In a high vacuum, a long straight filament sends electrons radially to a concentric cylindrical anode of radius $R$ cm. (about $\frac{1}{2}$ cm. radius, 10 cm. length). This magnetron is placed in a solenoid with the lines of force parallel to the filament. The magnetic field $H$ (0.1 to 500 gausses) of this solenoid bends the electrons in planes perpendicular to the filament. A milliammeter shows constant current flow from the filament to the anode until the magnetic field is increased to such a point that the electrons just fail to reach the anode, provided the accelerating potential $V$ (50 to 300 volts to the center of the filament) and the filament temperature are kept constant. When the electrons are thus bent away from the anode and return to the filament, the milliammeter reading suddenly drops to a very small value. The following equation then holds true:

$$e/m = 8V/H^2R^2.$$

$V$ and $H$ are to be in e.m.u. if e/m is to be in these units. Initial velocities of emission and the radius of the filament in comparison to that of the anode are neglected. Careful alignment of the filament, the axis of the anode and of the solenoid are necessary for a sharp break in the milliammeter reading. Take values of $H$ and $V$ when this reading is about half way down on the break.

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# CHAPTER 5

## THREE- AND FOUR-ELECTRODE VACUUM TUBES AND CRITICAL POTENTIALS

**Characteristic Curves and Van der Bijl's Equation.**

The flow of current from the hot filament to the cold plate of a two-electrode tube which has been evacuated to a high degree depends on the temperature of the filament and the accelerating potential applied to the plate as discussed in the third chapter. It was seen that for comparatively hot filaments and low plate potentials the current was limited because of the space charge, i.e., the negative charge density existing between the two electrodes. In 1907, Lee de Forest introduced a third electrode into the tube so that the stream of electrons from filament to plate passed through a wire grid. A negative potential (with respect to the filament) applied to the grid serves to retard the electrons while a positive potential tends to pull the electrons across, allowing greater currents to pass to the plate. Connections for observing this effect are shown in figure 5–1. Potentials $E_g$ applied to the grid are more effective in changing the plate current $I_p$ than changes of the plate voltage $E_p$. For example, in one type of tube an increase of one volt on the grid will increase the plate current by the same amount as would be caused by the addition of eight volts to the plate battery. *The ratio of change of plate potential to change of grid potential to cause equal changes of plate current is called the voltage amplification of the tube* and is designated by $\mu$.

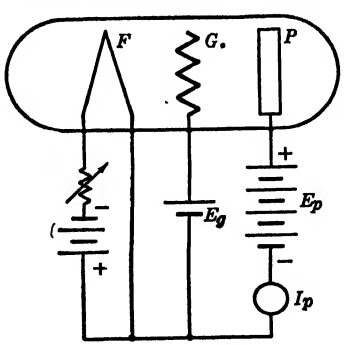


FIG. 5–1. A three-electrode vacuum tube.

Since the plate current is a function of (depends on) both the grid and plate voltages we may write

$$I_p = f(E_p + \mu E_g + \epsilon) \qquad (5\text{–}1)$$

in which $\epsilon$ is a small correction for the initial velocities of the electrons as they leave the filament, the contact potentials between filament and plate, etc., expressed in volts.*

Figure 5–2 shows a series of curves connecting these quantities which were obtained experimentally. For the curved, lower part

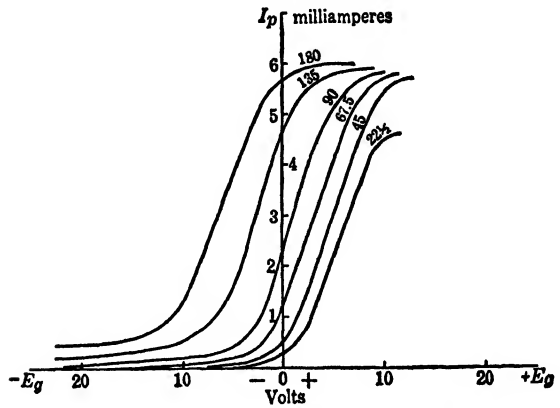


FIG. 5–2. Plate current vs. grid voltage.

of the curves, Van der Bijl was able to determine the function in the preceding equation.
This is

$$I_p = A(E_p + \mu E_g + \epsilon)^2 \qquad (5\text{–}2)$$

in which $A$ is a constant. The exponent is not accurately equal to 2 but is sufficiently close for most practical purposes. This equation does not apply to the straight part of the characteristic curves, i.e., to the region where a linear relation exists between plate current and grid voltage, nor does it apply to the upper knee where plate and grid voltages are great enough to draw over all electrons emitted by the filament. It is to be noted that as the grid is made

* When $E_g$ and $E_p$ are measured with respect to the center of the filament, $\epsilon$ is very small and may be neglected for most purposes. If there is an appreciable drop of potential along the filament, say five volts, the values of $E_p$ and $E$ may be taken as those of the batteries plus or minus two and one half volts, depending on the side of the filament to which the return wires of grid and plate are joined. In figure 5–1 half the filament drop is to be added to the voltage of the grid and plate batteries.

positive the number of electrons collected on it, as measured by the grid current, increases so that the plate current does not rise as rapidly as it otherwise would. The range over which Van der Bijl's equation holds true may be determined by plotting $\sqrt{I_p}$ as ordinates and $(E_p + \mu E_g + \epsilon)$ as abscissæ. The equation applies as long as the resulting curve is a straight line. $\epsilon$ may be obtained by making the plate voltage small and measuring the negative grid voltage required to reduce the plate current to zero. Then

$$0 = E_p + \mu E_g + \epsilon$$

$$\epsilon = -(E_p + \mu E_g) \qquad (5\text{–}3)$$

It is difficult to reduce the plate current absolutely to zero by this method but values so obtained will be sufficiently accurate since $\epsilon$ is a correction of only a few volts in most cases.

**The Amplification Constant $\mu$.**

If the plate voltage be increased from an amount $E_p$ to $E'_p$ it will be necessary to reduce the grid voltage $E_g$ to some value $E'_g$ in order to keep the plate current $I_p$ constant.

Then

$$I_p = f(E_p + \mu E_g + \epsilon) = f(E'_p + \mu E'_g + \epsilon)$$

from which

$$E_p + \mu E_g = E'_p + \mu E'_g$$

i.e.
$$\mu = \frac{E'_p - E_p}{E_g - E'_g} = \frac{\Delta E_p}{\Delta E_g} \qquad (5\text{–}4)$$

Thus a change of $\Delta E_g$ volts on the grid causes the same change of plate current as $\mu \Delta E_g = \Delta E_p$ volts introduced in the plate circuit. The value of $\mu$ depends on the construction of the tube. For the usual types of tubes

$$\mu = C\rho r n^2 + 1$$

in which $\rho$ is the distance between plate and grid, $r$ is the diameter of the grid wires, $n$ the number of grid wires per unit length and $C$ is a constant. The amplification constant ranges from 1 to 300 and may be measured by the method just described or by using

connections shown in figure 5–3. A 1000-cycle alternating current is impressed across the resistances $r_1$ and $r_2$ with the tube operating

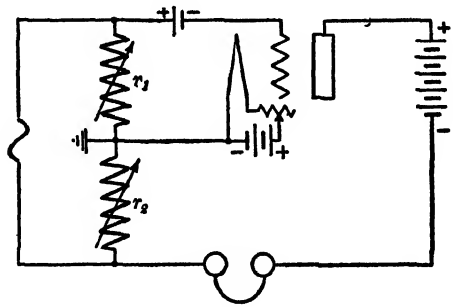


FIG. 5–3. Measurement of the voltage amplification constant.

at normal filament, grid and plate potentials. As a result, there will be a flow of current $I \sin \omega t$ through $r_1$ and $r_2$ resulting in a drop of potential through $r_1$ of amount $Ir_1 \sin \omega t$. This is superimposed on the grid voltage causing a change in the plate current, as indicated by the 1000-cycle note in the phones, which is equivalent to a change of plate voltage of amount $\mu Ir_1 \sin \omega t$. This may be counterbalanced by the voltage drop $Ir_2 \sin \omega t$ occurring across $r_2$. Thus $r_2$ is varied until no sound is heard in the phones, when

$$\mu Ir_1 \sin \omega t = Ir_2 \sin \omega t$$

$$\mu = r_2/r_1 \qquad (5\text{–}5)$$

$\mu$ is found to be essentially constant over considerable ranges of grid, filament and plate voltages.

**The Plate Resistance $r_p$.**

It has been found possible to treat the three-electrode tube, when used as an amplifier or oscillator, in a simple manner by replacing it with the circuit of figure 5–4 (the solid lines). Let a small change of potential $\Delta E_g$ be applied to the grid. This is equivalent to the addition of a voltage $\mu \Delta E_g$ ( $= \Delta E_p$) in the plate circuit which will increase or decrease the normal plate current by an amount $\Delta I_p$ according to whether it is in the same or opposite direction to the plate voltage. We may then write as a theorem,

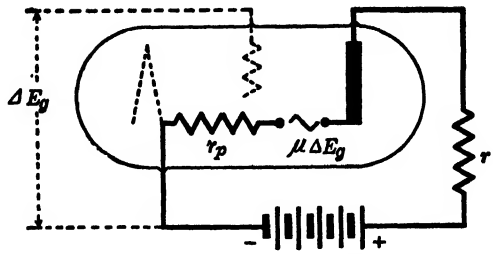


FIG. 5–4. Plate resistance of a three-electrode tube.

$$\Delta I_p = \frac{\mu \Delta E_g}{r + r_p} \tag{5–6}$$

where $r$ is the external resistance and $r_p$ the so-called plate resistance of the tube. This equation is true provided we interpret $r_p$ as

$$r_p = \frac{\Delta E_p}{\Delta I_p} \tag{5–7}$$

which is seen to be the reciprocal of the slope of the curve of figure 5–5 at the point $P$, the increments $\Delta E_p$ and $\Delta I_p$ being taken as small as possible. It is to be noted that this differs from the DC definition of resistance which would be the reciprocal of the slope of the line $OP$, i.e., $E_p/I_p$. Since the curve of figure 5–5 is never

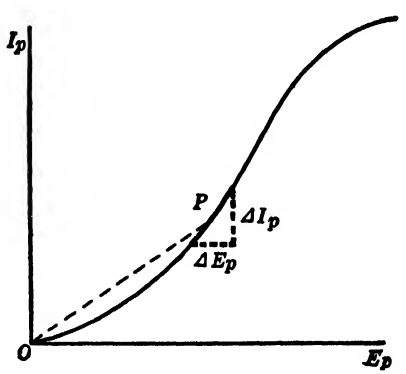


FIG. 5–5. Plate current–plate voltage curve of a three-electrode tube.

exactly a straight line, $r_p$ varies as the voltage of the plate battery is changed but, with fixed voltage, may be taken as a constant in applying equation 5–6.

Connections for measuring this output resistance are shown in figure 5–6 where normal plate, grid and filament voltages are used.

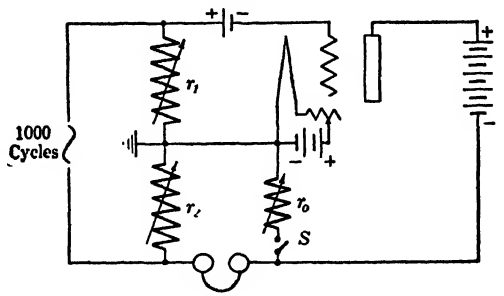


FIG. 5–6. Connections for measuring vacuum tube constants.

$r_1$ and $r_2$ are chosen arbitrarily, say $r_1 = r_2 = 10$ ohms, $S$ is closed and $r_0$ adjusted for minimum sound so that the potential drop across $r_0$ is the same as across $r_2$. Then

$$r_2 i_t = r_0 i_p = r_0 \left(\frac{\mu E_g}{r_0 + r_p}\right) = r_0 \left(\frac{\mu\, i_t r_1}{r_0 + r_p}\right)$$

from which

$$r_p = r_0 \left(\mu \frac{r_1}{r_2} - 1\right) \tag{5–8}$$

and if $r_1 = r_2$

$$r_p = r_0 (\mu - 1) \text{ ohms} \tag{5–9}$$

where $\mu$ is the amplification constant as determined for similar operating conditions.

**The Mutual Conductance $g_m$.**

The mutual conductance expressed in mhos is defined as the change of plate current per volt change on the grid. Thus

$$g_m = \frac{\Delta I_p}{\Delta E_g} \text{ mhos} \tag{5–10}$$

It is a measure of the effectiveness of voltage fluctuations on the grid in causing changes in the plate current. Dividing equation (5–4) by (5–7) shows that

$$g_m = \frac{\mu}{r_p} \tag{5–11}$$

Since $r_p$ changes with plate and grid voltages, so also does $g_m$.

**Vacuum Tube Voltmeters.**

Three-electrode vacuum tubes may be used to measure a wide range of voltages of any frequency. The plate and grid voltages are adjusted so that the tube is operating on the lower knee of its plate-current grid-voltage curve. When the grid is made less negative by the applied voltage, the plate current increases while with changes of grid potential in the opposite direction, there is zero or at most only a small decrease in the plate current. Hence, a meter in the plate circuit shows an increase whenever a potential, direct, low or high frequency, is applied to the grid. This meter may be calibrated in effective volts (the values given by ordinary voltmeters) when the instrument is first constructed, by applying known potentials. If the same filament, grid and plate potentials are always used, the calibration will hold good until the tube deteriorates (about 1000 hours of operation).

There are several types of these voltmeters on the market, designed to reduce the necessary batteries and having different connections to the recording meter. The Moullin type is shown in figure 5–7. The plate and grid voltages are secured from the potential drop in the filament and in the filament rheostat, so that the only operating voltage needed is a 6 volt filament battery. The resistance $R$ (30,000 ohms) tends to make the scale readings of the microammeter $G$ more uniform. The 1 mfd. condenser serves to by-pass the alternating component of the plate current. After the original calibration of the instrument, it is to be used in the following manner. The pointer of $G$ is adjusted to its mechanical zero, $A$ and $B$ are short circuited, the filament battery is connected and its rheostat varied until the pointer of $G$ reads zero (electrical) on the scale. Removing the wire between $A$ and $B$, the instrument is ready to use. The range of the instrument is from 0 to 1.5 volts in steps of 0.02 volts. There must be an external conducting path between $A$ and $B$. The instrument draws only a small current from the circuit under test.

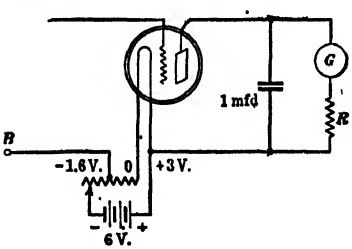


FIG. 5–7. The Moullin voltmeter.

The Hoare type is shown in figure 5–8 where the filament, grid and plate voltages are obtained from a common battery (6–24 volts) across the terminals *CD*. The resistances are adjusted so that, with *AB* short circuited, the pointer of the microammeter *G* reads zero. (Mechanical and electrical zeros are the same.) Calibration is then made and the instrument is ready for use. Always readjust *G* for zero by varying *R*, when the voltage across *CD* changes. The range is from 0 to 5 volts and the resistance of the instrument from 50,000 ohms to infinity. The instrument may be used with direct, alternating or high frequencies as a voltmeter or, by the use of a low resistance across *AB*, as a microammeter.

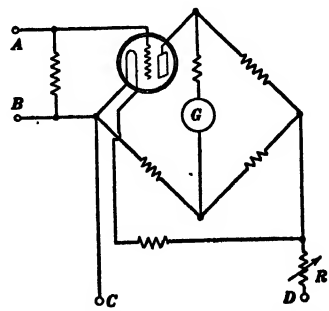

FIG. 5–8. The Hoare voltmeter.

The three-electrode tube may be used as a null instrument in measuring voltages when using the lower knee of the characteristic curve by increasing the grid potential sufficiently to reduce the plate current to its former small value. The DC voltage necessary to do this is the peak value of the potential being measured. (Effective or usual values equal 0.707 peak values.) A range up to 100 volts may be secured by this method.

Potentials as high as 50,000 volts may be measured when applied as the plate voltage ($E_p$) of a high amplification tube. The voltage on the grid ($E_g$) is made sufficiently negative to reduce the plate current to zero. Then $E_p = \mu E_g$. If $\mu = 1000$ and $E_g = 25$ volts, the unknown is 25,000 volts. Special tubes must be used which are long enough to prevent sparks between the plate and filament leads.

**Secondary Emission.**

It has been mentioned that whenever the grid is made positive a small part of the electrons are deviated from the plate circuit and flow back to the filament through the grid circuit. The amount of this grid current increases at first as the grid is made more positive as shown by *OA* in figure 5–9 after which it decreases to zero (*B*), flows in the opposite direction (to *C*) and finally returns to

zero and flows in the original direction. These effects are due to "secondary" electrons ejected from the grid wires by the electrons which reach it. The effective space charge is modified by the presence of these electrons. At *A* (Fig. 5–9) the secondary electrons become appreciable. Since the plate is more positive than the grid, they are drawn away from the grid. Thus electrons are both coming to and leaving the grid. When their numbers are equal, the net current is zero, as at *B*. With increasing positiveness of the grid, each incident electron has sufficient energy to knock out several secondary electrons, which are drawn over to the plate. With more electrons leaving than arriving, there is a flow of current opposite to the original direction. This negative current is shown as *BC* in figure 5–9. At *C*, the grid becomes sufficiently positive to draw back some of the secondary electrons. The grid becoming still more positive, the number of primary and secondary electrons reaching it soon exceeds the number escaping, as at *D*. It is to be noted that over the range *AC*, any *increase* of grid potential causes a *decrease* of electron flow to it. In other words the tube acts as a "negative" resistance just as in the case of arcs. In the latter, the phenomena are difficult to interpret because of the complex ionization taking place between the electrodes. Just as it is possible to use the variations of the resistance of an arc as a source of electrical oscillations (the singing or Poulsen arc), so also the phenomena of secondary emission may be used.

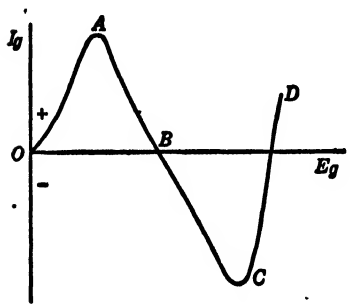


FIG. 5–9. Secondary emission.

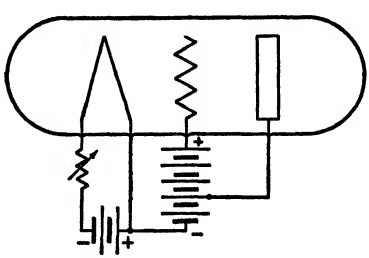

FIG. 5–10. A connection for studying secondary emission.

Secondary emission can also take place from the plate.* Thus

* Secondary electrons or delta rays are emitted by the anticathode of an X-ray tube due to the bombardment of the cathode rays.

in figure 5–10 the grid is made more positive than the plate and hence may be used to draw over to itself the secondary electrons emitted by the plate.

**Four-Electrode Tubes.**

The addition of a second grid to a three-electrode tube makes possible a further control of the space charges and hence of the plate currents. If the first grid ($G_1$ of figure 5–11) is made sufficiently positive to draw all electrons emitted by the filament towards it, relatively large currents can be obtained from the filament. While these electrons are passing over to the plate, they constitute a space charge between $G_1$, and $P$ which, being spread over considerable area, may be readily controlled by the second grid $G_2$. In this way, large variations of plate current are possible but secondary emission plays an important part in the phenomena and must be considered. Obviously, many circuit combinations are possible with such tubes in which either grid may act as the control with the other as an accelerator of the electrons. A detector-amplifier circuit is shown in figure 5–12.

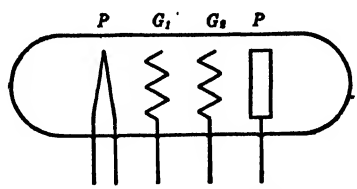


FIG. 5–11. A four-electrode tube.

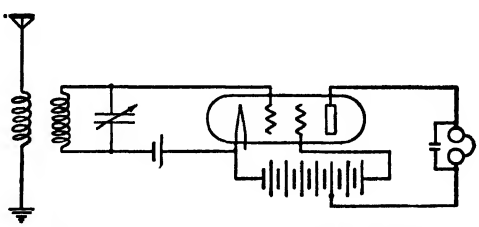

FIG. 5–12. A detector-amplifier circuit.

A further type of four-electrode tube has the second grid enclosing the plate as nearly as possible on all sides. This does not impede the flow of electrons to the plate but does shield the first or usual grid from voltage fluctuations on the plate. The capacity between the grid and plate (20 to 50 micro-microfarads in the ordinary tubes) is not of great importance at low frequencies but

is very important for radio frequency amplifiers. By the use of the extra grid around the plate, this capacity is reduced to a very small value. Oscillations set up in the plate current by voltage fluctuations on the usual grid (the one nearest the filament) are not then capable of effecting the potential of this grid. Hence the tendency of such a tube circuit to "go into oscillation" is made very small. Such "shield grid" tubes are constructed with high voltage amplification constants ($\mu = 100$ to 300) so that a large step up in voltage may be obtained with relatively few stages. Using metal shields between the tubes, amplification of the order of one million times has been obtained without the circuit going into oscillation. The limit of amplification is set by the shot effect, i.e., by the shock oscillations produced by the granular emission of electricity from the filaments.

**The Effect of Gases. — Ionizing Potentials.**

In the phenomena thus far discussed in connection with two-, three- and four-electrode tubes there has been assumed to be no gas present in the tube. Under such a condition the current-voltage curves showed a saturation value, all electrons emitted by the filament being drawn over to the plate as indicated by $AP_0$ in figure 5–13. The circuit for obtaining such a curve is given in

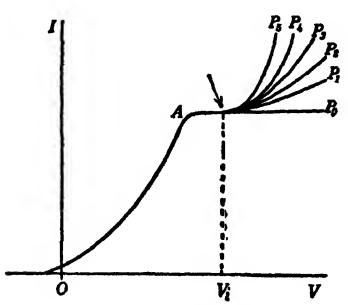


FIG. 5–13. The effect of gases in a two-electrode tube.

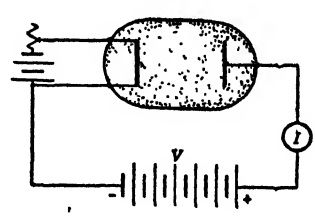


FIG. 5–14. Circuit for obtaining the curves in figure 5–13.

figure 5–14. If a gas such as helium at a pressure of one or two mm. is introduced in the tube, curve $OP_1$ results. The increase of current is due to the creation of ions when the electrons collide with neutral gas particles. The potential $V_i$, where this added current first

becomes evident, is one of the *critical potentials*. In particular, it is the *minimum ionizing potential*. If the distance between the filament and plate is less than one centimeter, the minimum ionizing potential is independent of the pressure if this remains less than two mm. for diatomic gases and ten mm. for monatomic gases. This may be shown by increasing the pressure, when the curves $OP_1$, $OP_2$, etc., may be obtained. These are found to rise above $OP_0$ at the same potential ($V_i$) as in the former case.

This method is not very satisfactory since the potential at which $OP_1$, $OP_2$, etc., rise above the gas-free curve $OP_0$ is not sharply defined. It may be brought out more clearly by heating the filament to such high temperatures that a space charge always exists between it and the plate. Now when positive ions and electrons are produced from neutral gas particles by collision, the electrons are rapidly drawn away and the slower positive ions tend to neutralize the space charge, resulting in much greater current flow. With the presence of a space charge, Langmuir's equation $I = CV^{\frac{3}{2}}$ holds true. Hence plotting $I$ against $V^{\frac{3}{2}}$ gives a straight line. As ionization by collision sets in, there will be a deviation from this straight line as indicated in figure 5–15. This "kink" is more pronounced than the one in figure 5–13. Correction must be made for the initial velocity of emission of the electrons, contact potentials, filament drops of potential, etc.

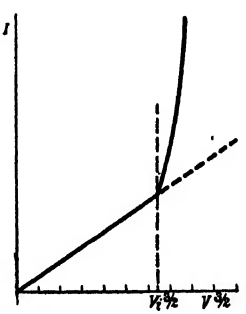


FIG. 5–15. Replot of data for figure 5–13.

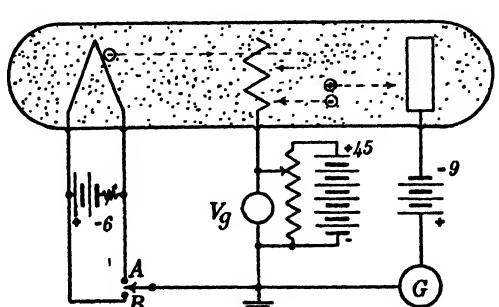


FIG. 5–16. Circuit for measuring ionizing potentials.

A better method of measuring the minimum ionizing potential involves the use of a three-electrode tube. The circuit is shown in figure 5–16. Here the grid is made positive so that electrons are accelerated toward it and pass into the space between grid and plate where they are reversed by a small negative potential on the plate and return to the grid. The voltage of the grid is increased so as to speed up the electrons until they have sufficient energy to ionize the gas between grid and plate. This is made known by observing the current flowing to the plate by means of the galvanometer $G$. Thus in figure 5–17 this "partial" or positive ion current begins to

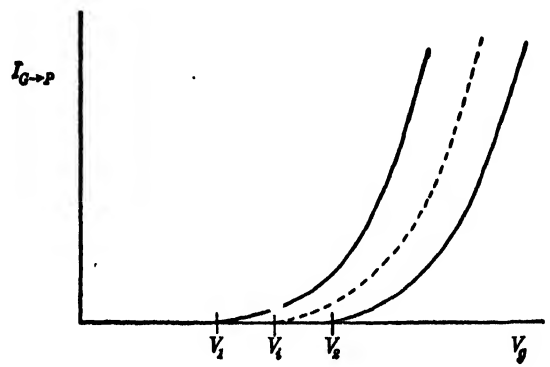


FIG. 5–17. Ionizing potential measurement.

flow when the grid is given a voltage $V_1$ or $V_2$, according to whether the switch is on $A$ or $B$. The two curves are taken in order to correct for the potential drop in the filament. The ionizing potential $V_i$ (uncorrected for emission velocity) is the mean of $V_1$ and $V_2$.

**Interpretation.**

The high velocity electrons may be deflected (elastic impact) on approaching a neutral atom or they may give up their energy to the atom. This latter will disturb the normal positions of the electrons in the atom, changing the energy from a value $E_1$ to a value $E_2$ by an amount

$$Ve = \tfrac{1}{2}mv^2 \qquad (5\text{–}12)$$

where $V$ is the accelerating potential and $e$, $m$ and $v$ the charge, mass,

and velocity of the incident electrons, respectively. If the energy of the incident electron is sufficiently great, i.e., is equal to or greater than $V_i\, e$, the atom will be ionized by the ejection of one of its electrons. This ionizing potential $V_i$, expressed in volts, gives a measure of the energy required to remove the most loosely bound electron from the atom and hence is numerically equal to the energy of this electron in its normal state in the atom.

**Radiation Potentials.**

¶If, in the case of impact, the kinetic energy of the impinging electron is not sufficient to drive the electron of the atom completely out, it will raise it to some higher level. In returning to its normal level the electron emits an amount of energy equal to that used in raising it. This appears in the form of an electromagnetic radiation corresponding to one frequency or wave-length in the X-ray, extreme ultra-violet, violet, visible or heat spectrum. The energy of the impinging electron is then the same as the difference in energy $E_2 - E_1$, between the two atomic states. This voltage is one of the critical potentials and is spoken of as a *radiation potential.* The quantum theory gives as the relation between the radiated frequency and the difference of energy,

$$h\nu = E_2 - E_1 \tag{5-13}$$

where $\nu$ is the frequency$(= c/\lambda)$, $\lambda$ is the wave-length radiated, $h$ is Planck's constant$(= 6.55 \times 10^{-27})$. From the last two equations

we get $$h\nu = V_r e$$

and therefore $$V_r = \frac{12344}{\lambda} \tag{5-14}$$

where $V_r$ is the radiation potential in volts and $\lambda$ the corresponding wave-length in angstrom units.

Radiation potentials may be determined with three- and four-electrode tubes containing gases by studying the various currents and potentials or by finding the potential across a tube which is just sufficient to cause the radiation of the corresponding spectral line.

## EXPERIMENT 5-1

### CHARACTERISTIC CURVES OF THREE-ELECTRODE TUBES

The connections are shown in figure 5–18. Three circuits are in-

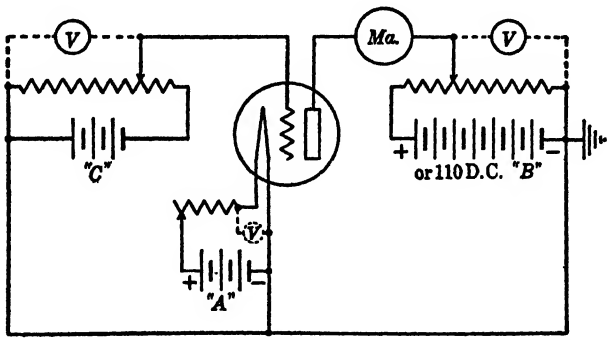


FIG. 5–18. Connections for obtaining the characteristic curves of three-electrode tubes.

volved, the filament, plate and grid, supplied by the A, B, and C batteries, respectively. It is desired to study the various currents in these circuits as the voltages are changed. However, to observe the principal phenomena involved, only three such relations need be observed. These are:

*Plate Current and Filament Voltage (or Current).*

Disconnect the grid circuit and join the plate and grid. Apply the normal voltage (say 45 for UX201A or CX301A tubes) to the plate. Vary the filament voltage in steps of about one-half volt from zero to normal (5). If filament currents are used, vary in steps from zero to normal (.25 amps.). Read filament voltage (or current) simultaneously with plate current and plot with the latter as ordinates.

*Plate Current and Plate Voltage.*

Disconnect the grid and plate and complete the grid circuit. Adjust the grid to zero potential and set the filament at normal voltage (or current). Vary the B battery voltage in steps of about three volts from zero to maximum (say 135) recording its value simultaneously with plate currents. Plot with the latter as ordinates.

*Plate Current and Grid Voltage.*

With connections as in figure 5–18, adjust the plate voltage (45) and filament voltage (5) to normal values. Note plate currents as grid voltages are varied from − 10 to + 10 volts. The points should be taken more frequently wherever the curves bend sharply. Repeat with various plate voltages, say 22½, 90 and 135, and plot all data on one graph with plate currents as ordinates. These are spoken of as the *static characteristic curves*. All will be shifted slightly if the A battery is reversed or the filament rheostat is connected in the other lead. If the plate voltage is small (10 volts) and the grid voltage high (vary it from zero to plus 90), *secondary emission* may be observed. Tubes using alternating current for heating the filament may be studied as above. The plate current-grid voltage curves will be straighter and have a smaller slope if resistances (5000 to 1,000,000 ohms) are included in the plate circuit because of the potential drop in them — but this is a phenomenon belonging to the plate circuit rather than to the tube itself.

## EXPERIMENT 5-2

## CONSTANTS OF VACUUM TUBES

Connections are shown in figure 5–6. The student should read the sections on amplification constant, plate resistance and mutual conductance given in the body of this chapter.

For measuring the amplification constant ($\mu$), switch $S$ is left open so that $r_0$ is not in use. Set $r_1 = 10$ ohms and vary $r_2$ until a minimum sound is heard in the phones. Apply equation 5–5. The 1000-cycle oscillator may be an electrically driven tuning fork with pick-up coils feeding into the circuit. Balance out the fundamental note only and keep the voltage drop across $r_1$ as small as possible.* $\mu$ is a constant for normal ranges of operating voltages but varies with unusual conditions. With all other parts of the

* These values are sometimes referred to as the geometrical amplification factors. If large resistances are added to the plate circuit, a study may be made of their effect on $\mu$ but this is a property of the circuit and not of the tube. With larger resistances, the voltage drop in them becomes an appreciable part of the B battery voltage so that the actual voltage on the tube is less. The values of $\mu$ so found are referred to as variation amplification factors.

circuit operating at normal values, change the plate voltage, then the grid voltage and then the filament voltage (or current), measuring $\mu$ over wide ranges. Plot with $\mu$ as ordinates.

For measuring the plate resistance ($r_p$) set $r_1 = r_2 = 10$ ohms, close $S$ and adjust for minimum sound in the phones. The value of $\mu$ to be used in equation 5–9 is that obtained for the same voltages by the preceding experiment. Measure the plate resistances with various tube voltages and plot.

Using equation 5–11, compute corresponding values of the mutual conductance ($g_m$) and plot.

## EXPERIMENT 5-3

### MINIMUM IONIZING POTENTIALS

The purpose of this experiment is to measure the minimum ionizing potentials of various gases such as nitrogen, hydrogen, helium and argon using three-electrode vacuum tubes.

Preparation of the tube may be made by the instructor or by the advanced student in the following manner. Secure a radio tube such as the UX201A and make a small hole in its top either with a flame or by cutting off the tip. Seal on a piece of soft glass tubing which contains a constriction a short distance from its end. Then seal this to a good vacuum system and evacuate until an electrical discharge can no longer be made to pass through the system. (Note: If the filament is left exposed to the air for more than a few hours, water vapor will ruin it.) Now admit a little of the gas to be tested and re-evacuate as thoroughly as possible. Let in a little of the gas again and start the evacuation but close off the system from the pumps when the pressure is around one-half mm. Anywhere from 1.0 mm. to 0.005 mm. will serve. The lower pressures are better although the amount of the positive ion currents measured will be small. The degree of evacuation may be crudely estimated by the distance between the striations. This will amount to about 1 mm. for a pressure of 1 mm. and 1 or 2 cm. for a pressure around 0.05 mm. The constriction is now closed, using as small a flame as possible, and the tube removed from the system. It is now ready for use.

Connect as in figure 5–16. The grid-voltage potentiometer should permit variations of 0.1 to 0.5 volts. A 3000 ohm

potentiometer will serve. The grid voltmeter should be accurate and should have a finely divided scale. The usual B and C batteries used in radio serve nicely for the grid and plate voltages. The galvanometer may be one of the usual wall type with a sensitiveness around $10^{-8}$ amperes and should be provided with a shunt.

With the switch on $A$ and normal filament current or voltage, slowly increase the grid voltage from zero, observing its values simultaneously with the deflections of the galvanometer. Plot with grid voltages as abscissæ and positive ion currents (galvanometer readings) as ordinates. A larger number of readings should be made where the galvanometer first shows a deflection. The galvanometer should be made as sensitive as possible in this region, no attempt being made to measure the large currents which are produced after ionization has set in. From the graph, determine the lowest grid voltage $V_1$ at which the galvanometer shows any deflection.

Repeat with the switch on $B$ to obtain the voltage $V_2$. The mean of these two is the minimum ionizing potential of the gas in the tube, neglecting corrections for the initial velocity of emission, contact potentials, etc. These usually amount to about one-half volt.

The experiment may be performed using the $AC$ tubes such as UX226 (low potential drop in the filament), when the values $V_1$ and $V_2$ will be closer together or by using $AC$ tubes of the UY227 type. In the latter, the emitting cathode is heated by an auxiliary filament operated on either AC or DC and hence is all at the same potential. The switch $AB$ is dispensed with and the final graph is like the dotted curve in figure 5–17.

Correction for initial velocities, etc., may be made if the tube is left on the vacuum system and filled with different gases. Be careful to re-evacuate and flush out with the new gas each time. A gas of known ionization potential is first used. The difference between the carefully determined experimental value and the correct value is the desired correction and may be applied to each of the succeeding gases.

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## CHAPTER 6

## THE PASSAGE OF ELECTRICITY THROUGH GASES AT REDUCED PRESSURES

**Introduction.**

• At atmospheric pressure a gas does not conduct electricity unless very high potentials are used or the gas is ionized by some agency such as X-rays, radioactive rays, or ultra-violet light. However, as the pressure is lowered it is found that a gas becomes conductive, reaching a maximum and then, at very low pressures again becoming an extremely poor conductor.

To study the passage of electricity through a gas while the pressure is being lowered, connect a vacuum pump and gauge (see Appendices B, C and D) to a long glass tube containing two metal plates sealed in with wires. The current from the secondary of an induction coil passes between the metal plates causing, among other things, the emission of light by the particles of gas left in the tube. When the pressure of the gas has been reduced to a few centimeters of mercury, a wavy streamer of light passes from one electrode to the other.

**The Geissler Discharge.**

As the pressure is reduced, the streamer broadens until it fills the entire cross section of the tube. At about one-half millimeter pressure, the conductivity is very good as may be shown by a spark gap in parallel with the tube. Unless the gap is very short, the electricity chooses the longer path through the discharge tube. The color of the light emitted depends on the gas in the tube, having a greenish color with mercury vapor, red with hydrogen, brilliant red orange with neon, yellow with helium, and brick red with nitrogen. A glow may be noticed on the cathode or negative electrode and close examination will show that it is separated from the electrode by a narrow dark space. Further examination will reveal a weakening of the light intensity on the far side of the glow.

These effects can best be understood by referring to figure 6–1 in which *H* is the anode, *A* the cathode and the various light and dark

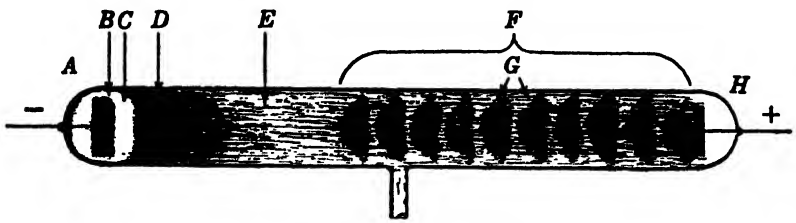


FIG. 6–1. The Geissler discharge.

places are named as follows: *B* is the cathode glow, *C* is Crookes' dark space, *D* is the negative glow, *E* is Faraday's dark space and *F* is the positive column which may contain striations *G*. In such a Geissler discharge, the positive column extends from Faraday's dark space to the anode, regardless of the length of the tube.

As the pressure is still further reduced, Crookes' dark space becomes more and more prominent. In other words, the negative glow moves away from the cathode. The length of this dark space may be used to form an idea as to the pressure of the gas in the tube. The longer it is, the lower the pressure, but an exact relationship cannot be given, as it varies somewhat with the shape of the tube and the kind of gas. Experience will soon allow one to estimate pressures fairly accurately by this method, or a given tube may be roughly calibrated by comparison with a pressure gauge such as that of McLeod. The length of Crookes' dark space will be about one centimeter when the pressure is 0.05 mm.

**Exploring Electrodes.**

It is obvious that in the use of metal probes for determining conditions inside the tube at various points, the presence of the electrode will disturb the normal currents and potentials. Langmuir has shown that electrons acquire such a high velocity in the tube that they will go to an electrode and increase its negative charge even though it is at a negative potential. Thus, an exploring electrode gives a measured potential which differs from the true one by as much as five to fifteen volts. To measure the potential at a point in the tube, increasing voltages are applied to the elec-

trode, which is negative at the start, and a curve of log.-current vs. voltage is plotted. More and more electrons can come in against the retarding field as its potential becomes less negative. The plot shows a straight line until the electrode potential just passes the potential at the point in question, when the slope suddenly changes, since electrons are no longer repelled and the positive ions, which formerly were collected, are now repelled. Potentials in a discharge tube may also be measured by means of a hot filament. Due to the fact that electrons can escape only when there is an accelerating potential, the potential of the space may be determined by varying the potential of the filament until emission just takes place.

**Normal Current Density.**

If a small current is passed through a Geissler tube, the cathode glow will cover only a small part of the cathode surface. If the current is increased, this luminous area extends until the whole surface is covered. It is found that the area covered is strictly proportional to the current, i.e., the current density (current per square centimeter) is a constant if the cathode is not completely covered. This is called the normal current density.

**Normal Cathode Fall of Potential.**

With all conditions giving normal current density, it is found that the potential drop measured from the cathode to a point in the negative glow remains the same. This is called the normal cathode fall of potential and has a characteristic value for every combination of gas and electrode material. For platinum and oxygen its value is 369 volts, for platinum and helium it is only 80 volts.

**Striations.**

Striations appear in the positive column whenever there is a mixture of gases. They are close together at higher pressures (0.1 to 1.0 mm.) and separate at lower values. Their separation may be used as a crude method of judging the degree of evacuation. With pure gases the positive column appears of uniform intensity unless viewed in a rotating mirror. It is then seen to be made up of striations moving with considerable velocity. In the case of argon,

the striations move from anode to cathode with a velocity between 1,000 and 10,000 centimeters per second.

**Theories.**

Many attempts have been made to interpret the phenomena in a Geissler discharge but none have succeeded completely because of the complex processes going on. It is sufficient at this time to state some of the conditions which exist. The potential gradient down the tube is not uniform. A large part of the potential drop occurs in Crookes' dark space, while slight jumps occur from striation to striation. There are groups of positive or negative ions clustered at various points. For example, the negative glow has a positive space charge. These arrangements, just like the potential distributions, are different from point to point in the tube. This means that the recombination and diffusion rates and the mobilities of the different ions must be considered and that the various ionizing and resonance potentials of the gases in the tube must be known. Part of the electrical energy sent into the tube disappears in the form of heat. In addition, there are charges of electricity formed on the inner surface of the glass tube. Also, it is found that certain gases are readily adsorbed by the electrodes, especially at the lower pressures.

**Rectifying Action.**

If one of the electrodes is small and the other is comparatively large, a rectifying action takes place so that the current passes in only one direction. The large electrode acts as the cathode. This phenomenon, which has been applied in rectifying tubes of battery eliminators, is due to the fact that a current much greater than the normal current density over the whole cathode cannot be passed through the tube without applying much higher potentials. Thus when the large electrode is negative, its large surface will allow a strong current to flow with normal potentials. However, when the small electrode is negative, a relatively small current will cause its surface to be completely covered with the negative glow. Greater currents require abnormal cathode falls so that the maximum reverse potential applied is only sufficient to cause a relatively small current to flow.*

* The direction of the current as discussed here is that of the electron stream and hence is opposite to that used in practice.

in all directions so that the plate, and to some extent the jar, become coated with a thin film of the metal. The other particles are electrons which leave the cathode at right angles and travel with high velocity, causing considerable heating of the plate and jar. These electrons may be deflected by a small magnetic field (10 to 25 gausses) so as to prevent overheating the plate. The sputtering is thought to be due to evaporation of the metal from small spots on the cathode surface which have been struck by ions falling through the large potential drop in Crookes' dark space. The ions come from the gas in the jar. Metals which sputter with difficulty in the residual air can be made to do so if certain gases, such as argon, are used. Gold, platinum, copper, iron, tungsten, silver and nickel may be deposited with comparative ease in the residual air, while aluminum and silicon are difficult to sputter. If Crookes' dark space touches the plate where the deposit is being formed, the cross gradient of potential sets up large currents in the thin metal, blistering it.

**X-ray Vacua.**

If the pressure is reduced until Crookes' dark space reaches the walls of the containing vessel, a fluorescence occurs, greenish, yellowish or bluish, according to the kind of glass. This fluorescence is due to X-rays and begins with pressures of the order of 0.01–0.001 mm. of mercury. Whereas current passes easily through the gas at higher pressures, it now becomes difficult for it to get through. Higher potentials are needed, since there is a scarcity of particles to act as carriers, unless a hot filament is used to supply them.

If high potential discharges from a condenser are passed between metal electrodes placed less than a millimeter apart in a vacuum around $10^{-4}$ mm., a brilliant flash of light is obtained.* This "hot spark" is a good source for use in the extreme ultraviolet (100 to 2000 angstroms). The radiations are characteristic of the atoms making up the electrodes and the gases occluded therein. Using the hot spark, various stages in the removal of the valence electrons of the lighter atoms have been studied by Millikan and his collaborators.

* A spark gap in air is used in series with the vacuum spark.

**Positive Rays.**

A faint streak of light may be seen back of a small hole in the cathode of a discharge tube evacuated to approximately 0.01 mm. This is caused by the positively charged and neutral particles which have passed through the hole and are colliding with molecules of the residual gas. The moving particles are called *positive (or canal) rays.** The charged particles or positive ions readily lose their charge as they move through the gas so that they are usually studied in a very good vacuum (0.001 mm. of mercury or less) by means of a willemite screen, photographic plate, thermocouple or Faraday chamber.

A photographic plate, placed some distance behind the cathode will be blackened at its center, as shown at *O* in figure 6–3, by the

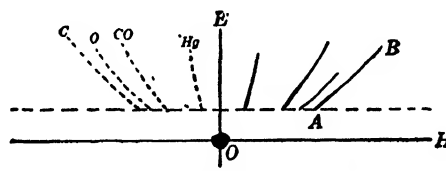


FIG. 6–3. Positive ray parabolas.

narrow stream of positive rays. If a magnetic field is applied across this stream, the spot will be deflected to the right or left, i.e., along *OH*. An electric field will cause deflections in a vertical direction *OE*, while the combined fields produce the various lines shown in the figure. It can be shown experimentally and theoretically that these lines are sections of parabolas whose foci are at *O*. Neutral particles in the positive stream are undeflected, leaving a record at *O*. The dotted lines on the left are obtained by reversing the magnetic field.

The spot at which a positive ion strikes the photographic plate depends on its mass, charge and velocity. Particles with the same ratio of charge to mass will fall on the same parabola. Their position in the parabola is determined by their velocity.

Since the positive ions start from different parts of the region in front of the cathode, they have different velocities and are,

* The name "canal rays" comes from the German "canal strahlen" meaning rays that have passed through small openings.

therefore, bent by different amounts. Those with minimum velocity will be bent the most and leave a record at $B$, while those falling through the maximum potential in the tube will be bent the least and leave a record at $A$. Since there are no particles with greater velocity, there will be no blackening of the photographic plate between $A$ and $O$.

The velocity of the positive rays can be measured by making use of Doppler's principle. As the positive ions move away from the cathode, they undergo energy changes which result in the emission of light. This light will show the usual spectrum of the element making up the gas in the tube. Wave-length measurements of one of these lines can be obtained from the side of the beam and from directly in front of it. Viewed end on, the wave-length from the moving particle is shifted toward the blue end of the spectrum as compared to that observed from the side. Say the end-on wave-length is $\lambda'$, that from the side is $\lambda$, then the Doppler shift is $\lambda - \lambda'$, and the velocity of the emitting source is

$$v = c\frac{\lambda - \lambda'}{\lambda} \qquad (6\text{–}1)$$

where $c$ is the velocity of light. The shift in wave-length in the case of the blue line of hydrogen ($H_\beta$) may be as great a five angstrom units. The velocity of the particles is thus found to be around $10^7$ centimeters per second; a value which is small compared with that of the electrons in the discharge tube.

If the region back of the cathode is maintained at a very low pressure by the continued action of a fast pump, it will be found that the beam of light decreases in intensity according to an exponential law. With hydrogen gas in the discharge tube, its intensity is practically zero, four centimeters behind the cathode. From this and the velocity of the ions, the maximum time duration of light emission from hydrogen ions has been computed as about $10^{-7}$ seconds.

J. J. Thomson has shown that the different parabolas (figure 6–3) are due to ions of differing charge to mass ratios. With methane gas present, parabolas are observed for the molecules $CH_4$, $CH_3$, $CH_2$, CH and the atoms of carbon and hydrogen, each charged positively by an amount equal to one electron. Occasionally molecular positive ions carry two charges, as in the case of $CO$.

The *atomic* positive ions often show several parabolas due to the loss of one or more valence electrons, i.e., they are singly, doubly or trebly charged. On rare occasions the ions become neutral and pick up a negative charge.

**Positive Ray Analysis and Isotopes.**

In studying the electric and magnetic deflection of neon positive ions, J. J. Thomson, in 1912, found two positive ray parabolas. It was thought that these might be due to $NeH_2^+$, $CO_2^{++}$ or to two kinds of singly charged neon atoms whose atomic weights were 20.0 and 22.0 (oxygen atomic weight = 16.000. The atomic weight of neon as determined by chemical means is 20.183). With refined technique, where different masses were more widely separated on the photographic plate, Aston showed that this latter viewpoint was correct. In other words, there are two kinds of neon atoms which are found mixed together in every sample large enough for chemical determination, in such amounts as to give 20.183. It is interesting that there should always be this ratio of neon 20 and neon 22 found in Nature. They are called *isotopes*, iso for the same and topos for place, as they are located together in the Periodic Table.

The existence of isotopes was known in radioactive substances in 1905, before the work with positive rays. This will be explained in Chapter 9. Isotopic substances, when once mixed, cannot be separated by the usual chemical and physical methods, although a slight separation has been accomplished in a few cases by prolonged diffusion through porous substances and by taking advantage of their s ght y different rates of evaporation.

Aston made an extensive and detailed study of the different atomic masses of the elements, using an apparatus diagramatically

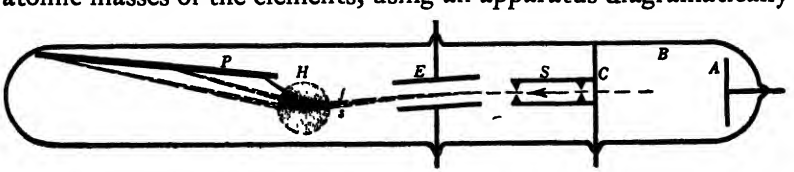


FIG. 6–4. Aston's positive ray apparatus.

presented in figure 6–4. An anode *A* and cathode *C* are sealed in the evacuated glass tube *B*. On maintaining a discharge between

*A* and *C*, positive ions are formed in the rarefied gas and pass through the hole in the cathode. They are confined to a narrow beam by the slits *S* and pass through the electric field *E*. The faster particles follow the line *f* and the slower ones move along *s*. They are then deflected by the magnetic field *H* so as to come to a focus on the photographic plate *P*. The apparatus is so arranged that rays of the same ratio of charge to mass but differing velocities are all brought to the same focal point, thus reducing the exposure times and assuring fine lines. Rays with different values of charge to mass ratio come to different focal lines. The dispersion of these lines is much greater than that attained by previous methods.

Dempster's method of studying positive rays is somewhat like the second method for determining $e/m$ for electrons as described in Chapter 4, except that larger magnetic field strengths are used (of the order of 5000 gausses). A small amount of the metal to be tested is vaporized in a furnace and bombarded by electrons so as to be ionized. The positive ions so produced are then accelerated by a known voltage and pass through a small slit into the magnetic field where they will be deflected to a second slit, provided the accelerating voltage and field strength have been properly adjusted. From here they fall on a metal plate connected to an electrometer. Altering the field strength, positive ions having different values of $e/m$ may be brought in succession to the second slit. Electrometer readings are proportional to the number of positive ions of each kind.

Practically all of the elements whose atomic weights are not whole numbers, oxygen being taken as standard at 16.000, consist of two or more isotopes whose atomic weights *are* whole numbers. For example, there are two kinds of boron (10 and 11), chlorine (35 and 37), argon (36, 40), iron (54, 56), etc.; while there are three kinds of magnesium (24, 25, 26), silicon (28, 29, 30), etc. Krypton has six isotopes while some elements have as many as nine isotopes whose atomic weights are whole numbers. It is interesting to note that these facts revert back to the old hypothesis that the different elements are constructed of different amounts of a common constituent. The hydrogen positive ions are never found with more than one charge. Hence the neutral atom has but one electron and one equally charged positive nucleus. This hydrogen nucleus, where the majority of the mass of the atom is concentrated,

is called *the proton*. It has been suggested that the heavier atoms are made up of equal numbers of protons and electrons, the alpha particle (nucleus of the helium atom) serving as an intermediate unit in atomic structure.

An objection to the foregoing statement may be made since the atomic weight of hydrogen is not exactly unity but is equal to 1.008 and since no isotopes have been found for this element. In addition, Aston's work in 1927, where the accuracy has been increased to one part in ten thousand, has shown that the atomic weights of many of the isotopes are *not* exact whole numbers. It is to be understood that these deviations from whole numbers are extremely small. They are explained by the "packing" effect. It is known from the scattering of alpha particles and Mosley's work with X-rays that the mass of the atom is concentrated near the center of the atom. From theories of electromagnetic mass it is known that the sum of closely packed "electrical" masses differs from the total of their isolated masses.

The *packing fraction* is defined as the difference of the atomic weight of the isotope and the nearest whole number, divided by the atomic weight and multiplied by 10,000. It is taken as positive when the atomic weight is greater than the nearest whole number. It is positive for the lighter elements and negative for the remaining elements, except for a few of the very heaviest.

The Relativity theory suggests that the radiation of a large amount of energy is accompanied by a loss of mass. This loss of mass is given as the loss of energy (in ergs), divided by the square of the velocity of light ($9 \times 10^{20}$). If, in the formation of helium from $4 \times 1.008$ grams of hydrogen, an amount of energy equal to $0.032 \times 9 \times 10^{20}$ ergs were radiated, we would expect the resultant helium to have a mass of exactly 4 grams. This possible source of energy has been suggested by astro-physicists to explain the radiant energy of the sun and stars.

## EXPERIMENT 6-1

### A STUDY OF THE DISCHARGE TUBE

The student should study Appendices B, C and D on the production and measurement of vacua and vacuum technique, before starting this experiment.

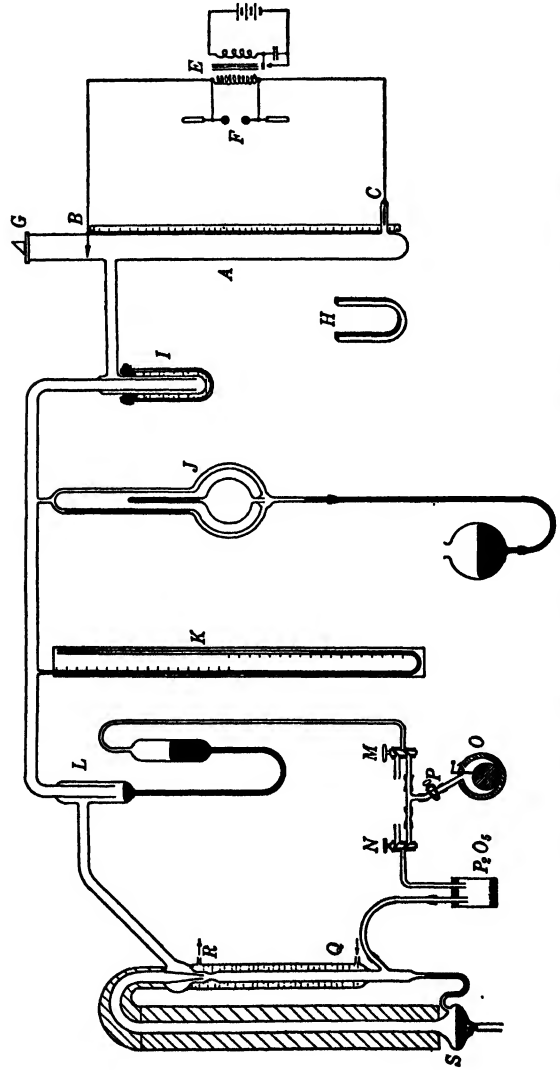


FIG. 6-5. System for studying the passage of electricity through gases as the pressure is reduced.

The purpose of the experiment is to become familiar with the phenomena accompanying the passage of electricity through a gas as the pressure is gradually diminished.

An oil pump, discharge tube and induction coil will show many of the phenomena, or a more elaborate set-up may be used as in figure 6–5. Here *A* is a discharge tube containing the metal electrodes *B* and *C*. *E* is an induction coil whose current is to pass through the tube and *F* is an alternate spark gap giving a measure of the resistance of the gas. When the gap must be made very short before the electricity prefers its path to the longer one through the tube, the resistance of the gas is small. *G* is a prism by which the positive rays which have passed through a small hole in the cathode *B* can be observed end on. The advanced student may make observations on the Doppler effect of the hydrogen blue and red lines of these rays. For this purpose, a spectroscope with high dispersion and large prisms is necessary, such as one having two prisms. The collimator and telescope should have lenses at least one inch in diameter and twelve inches in focal length. The velocity of the rays may be calculated from equation 6–1. *H* is a magnet by which the deflection of the various rays may be studied. The liquid air or $CO_2$ trap *I* need not be used unless low pressures and freedom from mercury vapor is desired. Pressures above one millimeter are determined from the difference between barometric height and the difference of level of the mercury in the two arms of the open tube manometer *K*. For lower pressures the McLeod gauge *J* is to be used. A description is found in Appendix C. The mercury valve (or stop cock) *L* is used to cut off the pumps from the system when the desired pressure has been reached. The mercury in the two arms of *L* is kept at the same level by turning the stop cocks *M* and *N* so that the oil (fore) pump *O* evacuates equally on the two sides. When the desired pressure has been reached, *M* is turned to admit air slowly through a capillary tube, depressing the mercury in the right tube of *L* and raising it on the left above the end of the inner tube. The pumps are again connected to the system by turning *M* and re-evacuating on the right side of *L*. Care must be taken that these changes be made slowly or mercury will be blown all through the system. The flask containing $P_2O_5$ serves to remove water vapor and to catch any oil which might be sucked out of the pump if the valve *P* had not been

turned to the outside air before the pump motor was turned off. When the pressure has been reduced as low as the fore pump can take it, turn on the water which runs through the jacket *QR*, of the condensation pump, then gently heat the mercury in the boiler *S*.

*Precautions.* — 1. Turn all stop cocks slowly.

2. Turn the cock *P* to the outside air before shutting off the motor of the oil pump.

3. Be sure the water is running through the jacket *QR* of the condensation pump.

*Experiment.* — Tabulate the following characteristics of the discharge tube phenomena for fifteen or more different pressures: length, intensity and color of the positive column, Faraday dark space, negative glow, Crookes' dark space, cathode glow; length of the alternate spark gap, the appearance of the cathode and positive rays and the effect of the magnetic field of a small magnet.

### EXPERIMENT 6-2

Measure the potential at various points in the tube.

### EXPERIMENT 6-3

#### SPUTTERING

Sputter an opaque surface of gold on a piece of glass or platinize a quartz fiber. The glass must be cleaned, first with potassium hydroxide (KOH), then with nitric acid ($HNO_3$), washed with water and dried before sputtering if the deposit is to be uniform. Quartz fibers are prepared by heating the tips of two quartz rods to white heat in an oxygen flame and drawing one of them across the other. The flame blows the fine threads away. To catch them, place a piece of cardboard, stuck full of pins, at an angle in front and a little above. To prepare an electrometer suspension, choose a fiber of appropriate length and fasten a small lug and a square hook of fine tungsten wire to its ends by means of small drops of shellac and lampblack. The lampblack serves to insure electrical contact between the tungsten and platinum coating which is to be sputtered on. Mount half a dozen fibers parallel to each other between the sides of a rectangle of stiff wire, holding them in place

with drops of shellac. The rectangle should have legs to support it in a horizontal position about one half an inch above the table. Place this in the sputtering apparatus about eight or nine centimeters from the cathode and reduce the pressure until the edge of Crookes' dark space is about half way between the cathode and the fibers. Using a one-half kilowatt, ten thousand volt transformer, a conducting coat of platinum should be secured in about thirty minutes. For gold the time will be about half that for platinum.

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## CHAPTER 7

## PROPERTIES OF ALPHA, BETA AND GAMMA RAYS

**Introduction.**

Certain substances, called the radioactive elements, make up a definite group of more than forty of the heavier elements. These have certain properties which clearly demarcate them from all others. Rutherford and Soddy have shown that there is a continual disintegration of these so that they are changing from one to another. Starting from two elements, called uranium and thorium, they change from one form to another, branch along three distinct paths and end in three isotopic forms of lead. These transformations are not affected by chemical changes, pressure, temperature or any other agency known to man at the present time. They occur at different rates, some taking but a small fraction of a second and others taking hundreds of years. These changes from one element into another are due to the spontaneous radiation of three kinds of rays, called alpha, beta, and gamma rays. The kind of ray emitted at the time of disintegration and its properties are characteristic of the element ejecting it. Many of these radioactive substances have been found by the discovery of new alpha, beta or gamma rays. A study of the properties of these rays and of radioactive transformations constitutes the remaining chapters of this book.

While experimenting in 1896 with uranium salts, Bequerel found that they emitted radiations capable of blackening a photographic plate after passing through bodies which were opaque to light. These radiations also have the ability to ionize a gas, making it a conductor of electricity. This offers an unusually satisfactory method for the detection of uranium and other radioactive substances. These radiations are also capable of producing scintillations on a luminescent screen.

**The Nature of Alpha, Beta and Gamma Rays.**

That alpha rays are positively charged and beta rays are negatively charged corpuscles while gamma rays are very short

electromagnetic radiations, may be determined by deflecting them with a magnetic field as in figure 7–1. (The deflections of the

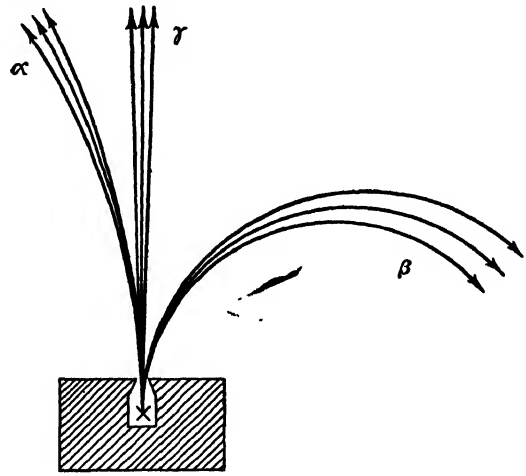


FIG. 7–1. Magnetic deflection of alpha, beta and gamma rays.

alpha rays are greatly exaggerated.) The gamma rays are undeflected, showing that they do not carry an electrical charge. The alpha and beta particles are deflected in opposite directions proving that they have opposite charges. From the direction of the magnetic field, the alpha rays are positively and the beta rays negatively charged.

By a method similar to that used in determining the charge to mass ratio of cathode rays, i.e., by magnetic and electric deflection, $E/M$ for alpha particles has been found to be 4823 e.m.u. per gram while their velocities vary between $1.37 \times 10^9$ and $2.06 \times 10^9$ cm. per second. There is a characteristic velocity for each of the radioactive substances as shown in table 6.

The measurement of the charge of an alpha particle consists in determining the total charge carried by a known number of particles. The total charge emitted by a given radioactive substance in a given time is determined by means of a Faraday chamber as in figure 7–2. The radioactive substance, located at $X$, sends out rays in all directions, some of which pass through the hole $A$ into the chamber $F$. The charge passing through the hole each second is to the total charge emitted as the area of the hole is to

the area of a sphere of radius $d$. Two precautions are needed in performing the experiment. First, the entire apparatus must be

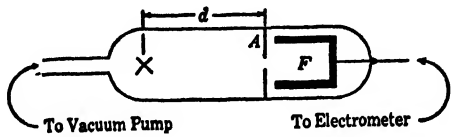


FIG. 7–2. Apparatus to measure the total charge per second.

evacuated in order to prevent the alpha particles from ionizing any gas through which they pass. Second, a magnetic field must be applied in order to retain all delta rays formed inside the chamber $F$ and keep out all which are formed outside. The delta rays are negative corpuscles knocked out of materials struck by alpha particles. If these precautions are observed it is found, for example, that a given sample of radium $F$ gives out $3.77 \times 10^{-4}$ e.s.u. of positive electricity each second.

Another method of determining the number of alpha particles emitted each second by a given radioactive substance is to measure the volume of helium which it produces in a known period, say one year. (It is shown below that the alpha particle consists of the nucleus of the helium atom.) Now Avogadro's number represents the number of particles in 22,414 cubic centimeters of a gas under standard conditions. Hence, the number given out in one year may be calculated.

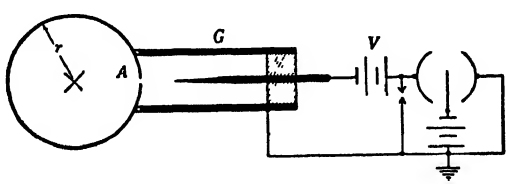


FIG. 7–3. Apparatus to measure the number of alpha particles per second.

The number of alpha particles emitted in one second may be counted directly by means of a Geiger counter. Figure 7–3 shows the connections when used with an electrometer, and figure 7–4

shows the connections when used with a vacuum tube amplifier.* The source of alpha rays is located at $X$ in the center of a ball of known radius, pierced by a very small hole of known area $A$. The Geiger counter $G$, which is placed over this hole, consists of a sharply pointed wire (platinum serves very well) supported along the axis of a metal tube by an insulating plug. If the wire is properly pointed and the accelerating potential $V$ properly adjusted, the entrance into $G$ of a single alpha particle is sufficient to give a deflection of the electrometer or to be heard in the phones. The process is an indirect one in which the alpha particle ionizes the gas in the counter and is recorded by the resulting ionization current. Thus, the number passing through the small hole each second may be counted. Then the total number leaving the radioactive substance each second is obtained by the proportionality of the area of the hole to the area of the sphere. In this way it is found that the sample of radium $F$ previously mentioned gives out 393,500 alpha particles each second.

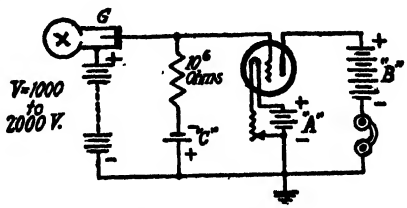

FIG. 7–4. Geiger counter and amplifier.

Another method for directly counting the number of particles is to observe the scintillations which they produce on a piece of diamond. At first, it was not known whether every alpha particle produced a scintillation, but comparison with the Geiger counter has shown this to be true.

Dividing the total charge ($3.77 \times 10^{-4}$ e.s.u.) by the number of particles ($3.935 \times 10^{5}$) gives $9.58 \times 10^{-10}$ e.s.u. as the charge on each. This is averaged with determinations made with other sources. It is then found that the charge of the alpha particle is twice that of an electron, although of opposite sign.

Now, for the alpha particle,

$$\frac{E'}{M'} = \frac{2e}{M'} = 4823 \text{ e.m.u. per gram} \qquad (7\text{–}1)$$

whereas for the hydrogen ion in solution we have $e/M = 9573$.

* The Geiger counter may be used for detecting any source capable of ionizing a gas.

Solving for $e$ and equating gives

$$M' = 3.970\, M \qquad (7\text{–}2)$$

i.e., the mass M′ of the alpha particle is 3.970 times the mass of the hydrogen ion in solution, which is the ratio, 4.00/1.008, of the atomic weights of helium and hydrogen.

That the alpha particle consists of a helium atom less two electrons, i.e., of a helium nucleus, has been verified by the following experiment. Radium emanation is collected in a tube $A$, figure 7–5, whose glass walls are only 0.01 mm. in thickness. The walls are then sufficiently thin so that the alpha particles from the emanation and its decay products can escape into the highly evacuated bulb $B$, which is made of glass sufficiently thick to stop them. When the emanation has first been introduced into $A$, no electrical discharge can pass from the mercury $C$ to the electrode $D$. At the end of a few days, the mercury is raised to compress any gas in $B$ into the capillary tube at the top. Then a discharge can be passed through the capillary which on examination with a spectroscope shows the complete helium spectrum. Thus when an alpha particle has slowed down it picks up two electrons and becomes an atom of helium. That the helium collected in $B$ is not due to a trace of this gas in the emanation is shown by filling $A$ with pure helium. Although left for a long time, no trace is found to leak through the thin walls into $B$.

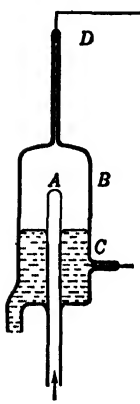


FIG. 7–5. The alpha particle is the nucleus of a helium atom.

Electric and magnetic deflection of beta rays shows that their ratio of charge to mass is the same as for cathode rays. Their individual charges being the same as for cathode rays, they are identified as high velocity electrons spontaneously emitted by the active substance. But their velocities are not all the same, even from one substance, ranging from 0.29 to 0.97 the velocity of light.*

* Since the mass of a body varies with velocity according to the law $m = m_0/\sqrt{1 - v^2/c^2}$, the ratio of charge to mass of different beta rays is not exactly the same.

The beta ray spectrograph of figure 7–6 is used to measure their velocities. In an evacuated metal box *A*, radium C or some other concentrated source of beta rays is placed at *S* in a lead block.

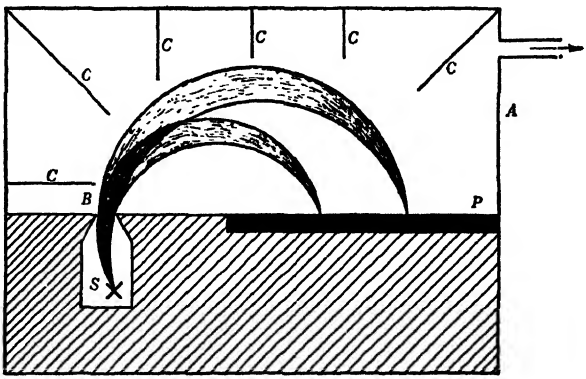


FIG. 7–6. Beta ray spectrograph.

The beta rays pass through a slit at *B* and are bent by a strong magnetic field perpendicular to the paper, coming to a sharp focus on a photographic plate *P*. Several metal shields *C* are used to cut off secondary beta rays created by the primary or gamma rays from *S*. The beta rays with least velocity are bent the most, giving lines on the plate near the slit and vice versa. A general fogging of the photographic plate shows a continuous radiation from *S* with an infinite number of velocities. This background is of unequal intensity along the plate. The velocity $v$ of the beta rays corresponding to a given line, distant $D$ from the center of the slit, may

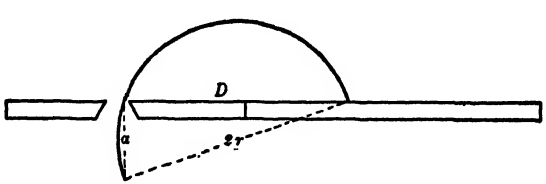


FIG. 7–7. Velocity measurement in the beta ray spectrograph.

be calculated as follows. The centrifugal force $mv^2/r$ on each electron (see figure 7–7) is balanced by the magnetic force $Hev$. The

relativity mass

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

is used, giving

$$v = \left(Hr\frac{e}{m_0}\right)^2\left(\frac{1}{1 + \frac{Hr}{c}\frac{e}{m_0}}\right) \qquad (7\text{–}3)$$

where $r = \frac{\sqrt{D^2 + a^2}}{2}$,

and $e/m_0 = 1.77 \times 10^7$ e.m.u. per gram,

$e = 4.774 \times 10^{-10}$ e.s.u.

and $m = 9.00 \times 10^{-28}$ grams.

A table is given in the back of the book for the velocities of beta rays from various substances.

If X-rays fall on an inclined plane of solid material at $S$, figure 7–6, electrons are emitted whose spectrum may also be obtained by this method. In this way, the energy of tightly bound electrons around the nucleus of atoms can be studied. The method may also be used to study photo electrons emitted by solid substances irradiated with ultra-violet light, and the secondary or delta rays ejected from a solid when struck by beta rays or primary electrons from some source such as a hot filament.

In practically every case where a beta particle is ejected from an atom, gamma rays are also emitted. These are composed of rays characteristic of the active material as well as a continuous spectrum and range from 1.365 to 0.0047 angstrom units.

**Ionization by Alpha, Beta, Gamma and X-rays.**

C. T. R. Wilson has shown that small drops of water will form on dust particles or ions in a saturated water vapor which has been suddenly expanded. If, with all dust particles removed, an alpha particle passes through a saturated vapor at the time of expansion, its path may be observed by the water drops formed on ions which it has created in the vapor. From these tracks, it is found that the alpha particle produces an intense ionization along a straight path. The ionization is so great that the water drops combine to give a

single line. Occasionally the line is sharply bent, indicating a definite deflection of the alpha particle. Ordinarily the alpha particle is able to plunge through the outer electrons of an atom, driving them out without suffering any deflection itself, but occasionally it passes so close to a nucleus that it is deviated from its straight path.

If an alpha ray, consisting of many alpha particles confined to a narrow pencil, is studied, it is found that nearly all of the particles travel a certain distance beyond which the number decreases rapidly as indicated by figure 7–8. The number is determined by counting the scintillations per minute on a fluorescent screen set up in the path of the ray. It has been pointed out previously that one scintillation occurs for each alpha particle. The alpha particle may be thought of as gradually losing energy in its passage through the gas until it is too slow to penetrate any more atoms and make any more ions. Although it is slower toward the end of its path, it is most efficient as an ionizer just before the

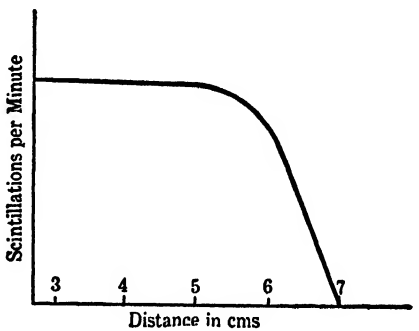


FIG. 7–8. The number of alpha particles penetrating a gas to a given distance.

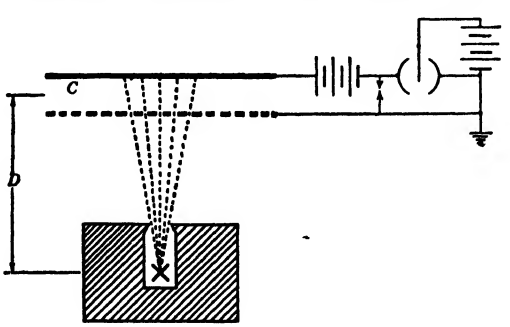


FIG. 7–9. Apparatus for determining the curve in figure 7–10.

end. This phenomenon may be studied with the apparatus in figure 7–9. In this, the alpha particles from the source $X$, in a lead

shield, traverse the distance $D$ to a shallow ionization chamber $C$ (having a wire gauze for its lower plate) where they produce ions which are measured with an electrometer. The distance $D$ is varied and a series of points on the curve in figure 7–10 obtained. From this it is seen that there is much greater ionization of the gas near the end of the range of alpha particles of a homogeneous beam than along the track. The area under this curve gives the total number of ions produced by the beam in a given gas at fixed temperature and pressure. This number varies with the speed of the alpha rays. For example, an alpha particle from polonium produces $1.6 \times 10^5$ ions and those from radium C produce $2.4 \times 10^5$ ions. The general shape of the curve in figure 7–10 is not altered by change of temperature or pressure or the kind of gas used, although its absolute value is altered.

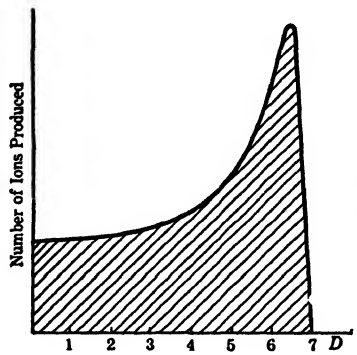


FIG. 7–10. The ionization produced by an alpha ray at various distances along its path.

Using the method of expanding a saturated vapor, tracks of beta particles have been observed. The ions produced are spread throughout an appreciable volume of the gas and not concentrated as in the case of alpha particles. This is due to the tortuous path of the beta particles. Although possessing approximately ten times the velocity of the alpha particles, they have such small mass, and hence such small momentum and energy, as to be easily deflected in their encounters with gas atoms. Sometimes they undergo a series of small deflections and at other times suffer radical changes in direction. Furthermore, several beta rays with different velocities leave any one substance so that a homogeneous beam cannot be had without the use of magnetic or electric fields and consequent diminution in intensity. However, the total number of ions produced by beta particles from a substance emitting all three rays is much less than the number created by the alpha particles (about one one-hundredth).

The ionization due to gamma rays is much less, about one one-

hundredth of that produced by the beta rays from the same source. The ions are more diffusely spread throughout the gas. This may be seen in cloud expansion experiments.

The cloud expansion apparatus may also be used to study the passage of X-rays through gases. It is found that ionization by X-rays is an indirect process where the rays knock electrons out of the gas atoms. These electrons produce the major portion of the ions observed. It is interesting in this connection to point out that the scattered X-rays which come off at an angle whenever a beam of X-rays pass through gases or other matter are of longer wave-length than the original X-rays. This is known as the Compton (A.H.) effect, after its discoverer. The altered wave-length may be accounted for on a theory that considers the exchanges of momentum and energy between the X-rays and the electrons in the atoms. In fact, a satisfactory formula * is obtained by considering the X-rays to consist of bundles of energy of amount $h\nu$ where $\nu = c/\lambda$. At a collision, this bundle may give some energy to the electron causing it to recoil while the X-ray itself is scattered with diminished energy and consequently lower frequency or longer wave-length.

**Range of Alpha, Beta and Gamma Rays.**

Gamma rays are more penetrating than X-rays and, with the exception of cosmic rays, are the most penetrating known today. They will pass through a block of iron one foot thick. Beta rays, however, are practically all stopped by three mm. of lead. No definite range can be assigned to beta rays since they emerge from the substance with different velocities and follow such tortuous paths. The alpha rays have the shortest range of all, being stopped

* The modified wave-length $\lambda$ is given by

$$\lambda = \lambda_i + \frac{h}{mc}(1 - \cos\phi) \qquad (7\text{–}4)$$

where $\lambda_i$ is the incident wave-length, $h$ is Planck's constant, $m$ the mass of an electron, $c$ the velocity of light and $\phi$ the angle between the scattered beam and the direction it would have taken if the electron were not there. This formula has been verified experimentally using an X-ray spectrometer and also by observing the predicted angle of recoil of the electrons by means of an expansion chamber.

by 8.52 cm. of air (at 76 cm. pressure and 15° C.), 0.006 cm. of aluminum or a sheet of writing paper. *The maximum range of the alpha particles from any one radioactive substance is a characteristic constant by which that substance can be distinguished from all others.*

The maximum range of an alpha particle can be determined by using the apparatus in figure 7–9, plotting a curve as in figure 7–10. The intercept on the *D* axis gives the range. Another method is to observe the scintillations produced on a fluorescent screen placed in the path of the rays, as indicated in figure 7–8. It is not necessary to count the number of scintillations per minute but only to observe the maximum distance to which the screen may be moved from the source before the scintillations disappear. This method yields results some two or three mm. shorter than that obtained by the electrical method since the rays are not so effective in producing scintillations near the end of their range. Now the range varies directly as the absolute temperature and inversely as the pressure of the gas through which the rays pass, i.e., inversely as the number of gas molecules passed through. By observing the range of the alpha particles at different pressures and temperatures with a fluorescent screen or metal plate connected to an electroscope or electrometer, it is possible to calculate the range under standard conditions, i.e., 76 cms. of mercury and 0° C.

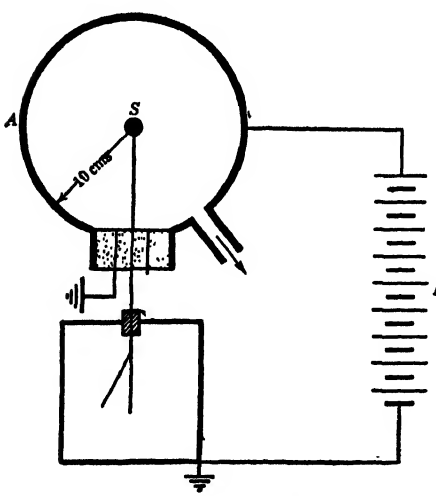


FIG. 7–11. Electrical method for measuring the range of alpha particles.

A third method, due to Geiger and Nutall, for measuring the range of alpha particles uses the apparatus illustrated in figure 7–11. The source of alpha particles is located at *S* in the center of a charged metal sphere *A* whose radius is greater than the maximum range at atmospheric pressure. The battery *B* has sufficient potential, say 700 volts, to draw over to the ball all ions pro-

duced (the shaded area of figure 7–10). As the pressure in the ball is reduced, the alpha particles are able to reach its walls and at still lower pressures would go beyond, were it not for the walls. The ionization current as measured by the electroscope is fairly constant as the pressure is decreased, until after the particles have begun hitting the walls. It then falls off markedly since the particles are not producing as many ions as they are capable of doing. In figure 7–12, the kinks in the curves indicate the pressures at which the alpha particles have a range equal to the radius of the ball. Two kinks in the curve indicate two sets of alpha particles of different ranges coming from two radioactive substances.

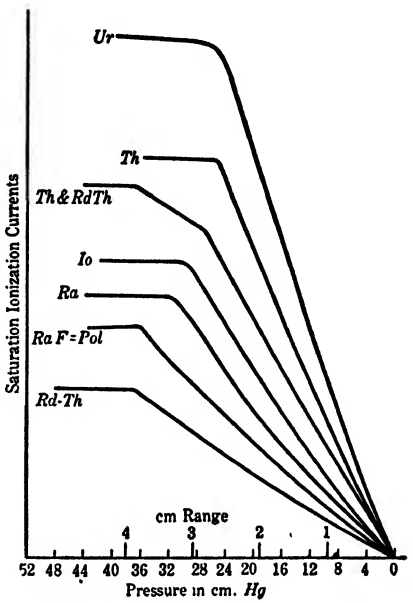


FIG. 7–12. Results from the apparatus of figure 7–11.

There are a few *general laws* found to apply to all radioactive substances. One of these relates the initial velocity $v$ and range $R$ of alpha particles. It is

$$v^3 = aR \tag{7–5}$$

where $a$ is a constant.

Another general law of radioactivity connects the life of the substance with the range of the alpha particles emitted. If $\lambda$ is the fractional number of atoms breaking up each second ($= 0.693$ divided by the time $T$ for one half of a given amount of radioactive substance to change into its next element), then

$$\log \lambda = A + B \log R \tag{7–6}$$

where $A$ and $B$ are constants. This important law is shown graphically in figure 7–13 for the uranium-radium series while the accom-

panying table gives the values of λ (the transformation constant) and the range of the substance. There are similar lines for the other two families of radioactive substances. The two laws above may be stated in the form: *an unstable atom has a short life, sending out long range, high velocity alpha particles.*

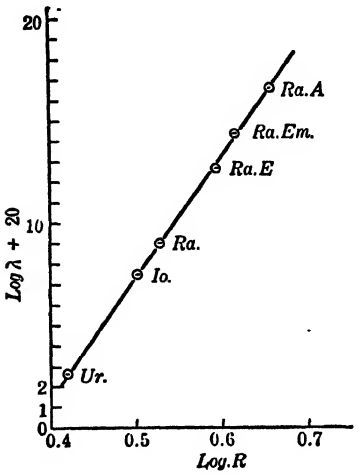


FIG. 7–13. A short life substance sends out long range alpha particles.

The constants $A$ and $B$ may be computed from two known values of λ and $R$. $A$ is different for the three radioactive series, but $B$ is essentially the same for all. By measuring the range of the alpha particles from a given substance and applying this law, one may compute the transformation constant λ and the half period T. Thus, for RaC′, λ has been found to be $8.4 \times 10^5$.

| Substance | | λ (sec$^{-1}$) | Range in Air (76 cm. 15° C) |
|---|---|---|---|
| Uranium I | UI | $4.7 \times 10^{-18}$ | 2.48 cm. |
| Uranium II | UII | $10^{-14}$ (?) | 2.87 |
| Ionium | Io | $3.2 \times 10^{-13}$ | 2.98 |
| Radium | Ra | $1.30 \times 10^{-11}$ | 3.27 |
| Radium F (= Polonium) | RaF (Po) | $5.90 \times 10^{-8}$ | 3.74 |
| Radon (=Ra. Emanation) | Rn (RaEm) | $2.085 \times 10^{-6}$ | 4.12 |
| Radium A | RaA | $3.85 \times 10^{-3}$ | 4.70 |
| Radium C′ | RaC′ | $10^{6}$ (?) | 6.86 |

**H-Particles.**

It has been found that extremely long range, positively charged particles are knocked out of many of the elements when bombarded by high speed alpha particles. The ranges of these particles and their deflections in magnetic and electrostatic fields have been studied.* They have been identified as the proton or nucleus of the hydrogen atom, and are called H-particles. The following values (International Critical Tables, Vol. I, p. 365) give an idea of their range when ejected from various substances.

| Element | Forward Range in cm. | Backward Range in cm. |
|---|---|---|
| B | 58 | 38 |
| N | 40 | 18 |
| F | 65 | 48 |
| Na | 58 | 36 |
| Al | 90 | 67 |
| P | 65 | 49 |
| Mg, Si, S, Cl, A, K | 18–30 | |
| Ne | 16 | |

It is seen that those ejected in the same direction as the alpha particles have greater range than those in the opposite direction. The number of H-particles emitted is small in comparison to the number of bombarding alpha particles (one or two in a million). Such disintegrations have, however, been observed with the cloud expansion apparatus. By comparisons of these long range particles, it is found that the nuclei of the light elements having an odd atomic number are less stable than those of even number.

Although the subject of the absorption of various rays will not be given until the next chapter, it is included with the other properties in the following table.

* By Rutherford and Chadwick, Kirsch and Peterson, in particular. Marsden was the first to observe these long range particles.

SUMMARY OF RADIOACTIVE RADIATIONS

| Rays | Alpha | Beta | Gamma |
|---|---|---|---|
| Nature | Helium nuclei or $He^{++}$ | Electrons | Very short electromagnetic radiations |
| Charge | $+2e$ | $-e$ | None |
| Charge/Mass | $\frac{2e}{4M} = 4832 \frac{\text{e.m.u.}}{\text{gram}}$ | $\frac{e}{m} = 1.77 \times 10^7 \frac{\text{e.m.u.}}{\text{gram}}$ | |
| Velocity | $1.39 \times 10^9$ to $2.06 \times 10^9 \frac{\text{cm.}}{\text{sec.}}$ about $\frac{1}{10}$ that of beta rays. | $0.29c$ to $0.96c$ or $0.87 \times 10^{10}$ to $2.88 \times 10^{10} \frac{\text{cm.}}{\text{sec.}}$ | $3 \times 10^{10} \frac{\text{cm.}}{\text{sec.}}$ |
| Ionization | Great; along straight, narrow beams | Moderate; curved trajectories | Small; throughout the gas. |
| Range | 2.37 to 8.16 cm. in air (76, 0°C) | | |
| Absorbed | Easily; 0.006 cm. aluminum | Moderately; 3 mm. lead $\mu$ = 13.1 to 5500 in aluminum | With difficulty; 25 cm. iron. $\mu$ = 0.096 to 585 in aluminum. |
| Wave-length | ..... | ..... | 1.365 to 0.0047 angstroms |

## EXPERIMENT 7–1

### RANGE OF ALPHA PARTICLES — SCINTILLATION METHOD

The apparatus for measuring the range of alpha particles at various pressures is shown in figure 7–14. An oil pump is connected to the stop cock *A*, partially evacuating the glass tube *B* (about 20 cm. long, 3.5 cm. diameter). The pressure in the tube is determined with the open-tube mercury manometer *C*. The pressure in centimeters of mercury is equal to the difference between the barometer reading and the difference in height of the mercury in the two arms. Air may be admitted to the tube slowly through the capillary *D* and stop cock *E*.

The active material is on a small metal plate $F$, fixed with soft wax to a second plate supported by a long metal tube. This may

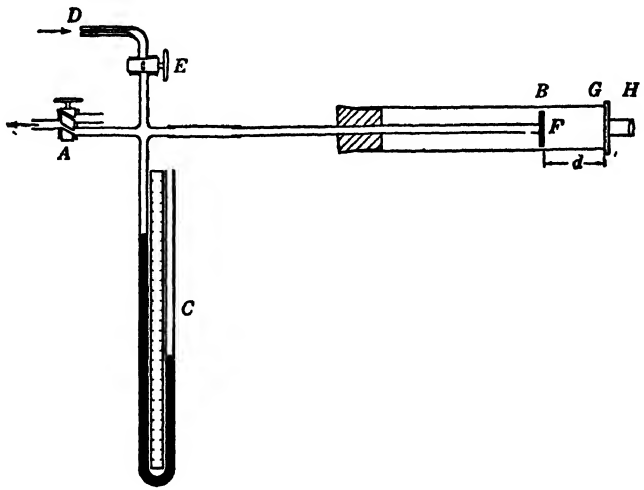


FIG. 7-14. Scintillation method of measuring the range of alpha particles.

be slid in and out through a rubber stopper. There is a small hole near the end of the tube to allow evacuation of $B$. The active material may be any substance emitting alpha particles but, because of the contamination of the walls of the tube by disintegration products or by recoil atoms, only certain substances should be used. A good source consists of ionium. Another may be made from the old, crushed tubes of the active deposit of radium used in medical work. These "needles" were originally filled with radium emanation which changed in the course of a few weeks through the short-life, active deposit to become radium D with a comparatively long life. Radium D is continually producing radium F or polonium (after an intervening substance) and this sends out the alpha particles whose range is to be measured. The metal disc is placed in a horizontal position and coated with a thin layer of water glass (sodium silicate). While this is drying, two or three pulverized radium D tubes are sprinkled over its surface. When dry it is ready for use.

The fluorescent screen $G$ is prepared by placing the glass plate

in a horizontal position, covering with a thin layer of water glass and sprinkling uniformly with a mixture of phosphorescent zinc sulphide and calcium tungstate as it drys. About 20% of the former and 80% of the latter has been found satisfactory. When dry, the plate is sealed to the end of the tube with sealing wax, the luminescent material being inside. Scintillations produced by those alpha particles which reach this screen are observed through a small lens *H*.

*Notes.* — 1. Turn the stop cock *A* to admit air to the oil pump before shutting off its motor; otherwise oil may be sucked up into the system.

2. The experiment must be performed in a good dark room. It will be necessary for the observer to remain in the dark at least ten or fifteen minutes to accustom his eyes to the darkness and to allow the screen to dim down before the scintillations will be sufficiently bright for accurate work. A second student should read the manometer and manipulate the stop cocks, using a shielded ruby light.

3. There are always a few scintillations occurring at more or less rare intervals on the screen. These are to be disregarded.

4. Do not touch the surface of the active material with the fingers.

*Procedure.* — Read the barometric pressure and the temperature at the beginning and end of this experiment. Use the average value in the calculations.

Set the source at a distance *d* (see figure 7–14) which is to be about one centimeter greater than the range of the particles at atmospheric pressure. Record the value of *d*. When the eyes have become accustomed to the darkness, lower the pressure slowly until the scintillations first appear. Note this pressure. Lower the pressure still farther, then let it increase slowly and observe the pressure when the scintillations first cease. Repeat these steps eight or ten times and average all values to find the pressure corresponding to the range *d*.

Repeat with the source at various distances farther away from the screen.

From the relation that the range is inversely proportional to

the pressure and directly proportional to the absolute temperature, compute the range at 76 cm. and 0° C. from each set of data. Average these readings and compare with the accepted value.

The final value will be found to be somewhat smaller than the accepted range because of absorbing films such as grease from the fingers, thin layers of water glass, etc., and because it is difficult to distinguish between the spurious scintillations and those of the alpha particles of maximum range.

### EXPERIMENT 7-2

### RANGE OF ALPHA PARTICLES — ELECTRICAL METHOD

Measure the range of alpha particles from polonium using the apparatus of figure 7–11.

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## CHAPTER 8

## THE ABSORPTION OF VARIOUS RAYS

**Introduction.**

Alpha rays are absorbed * easily; gamma rays, with difficulty, while beta rays are intermediate. The absorption of these rays by a solid substance, such as aluminum, may be measured by placing an appropriate radioactive substance in an electroscope, as at *XXX* in figure 8–1. Observe the rate of fall of the leaf as various thicknesses of aluminum and lead are placed over *X*. First, using thin sheets of aluminum foil, the observed rate of fall measures the ionization produced by the alpha, beta and gamma rays, i.e., the combined activity of the three rays. As additional sheets of foil are placed over the source, the alpha rays are successively decreased but the other two are practically unaffected. With about 0.006 cm. of aluminum, nearly all the alpha rays are absorbed. The beta rays may now be reduced by

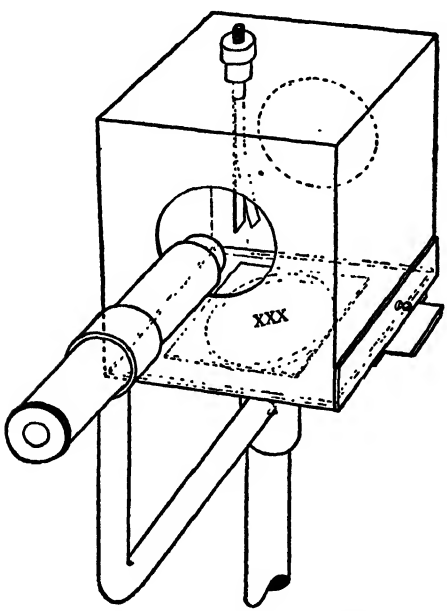


FIG. 8–1. An alpha ray electroscope.

* The intensity, at a great distance from an unshaded light bulb, is less than that near the bulb for two reasons; first, the spreading out in all directions, which follows the inverse square law, and second, absorption by the air following the exponential law discussed in this chapter. Only this latter type of absorption occurs for the parallel rays of a search light penetrating a fog. The decrease which follows the inverse square law is not considered in this chapter, as all measurements are made with comparatively thin absorbers.

successive additions of aluminum sheets, 0.01 cm. thick. A sheet of lead approximately 3 mm. thick will absorb all the alpha and beta rays. Adding such lead sheets will now serve to show the absorption of gamma rays alone.

That thickness of a substance, such as aluminum, which will produce the same absorption as one centimeter of air under standard conditions of pressure and temperature is called the *equivalent absorbing power.* It is a constant for a given material absorbing a given ray but differs for different rays.

The *stopping power* of a substance for alpha rays is the thickness of air which will reduce the range by the same amount as the given thickness of material. The stopping power is proportional to the square root of the atomic weight of the substance. For example, the oxygen atom is four times as effective as the hydrogen atom in reducing the range of alpha particles.

**The Absorption Law for Beta and Gamma Rays.**

For the beta and gamma rays from a radioactive substance, the intensity $I$ of the beam after passing through $d$ cm. of the absorber is

$$I = I_0 \epsilon^{-\mu d} \qquad (8\text{–}1)$$

where $I_0$ is the original intensity and $\mu$ is the *coefficient of absorption.* The intensities are measured by the amount of ionization which

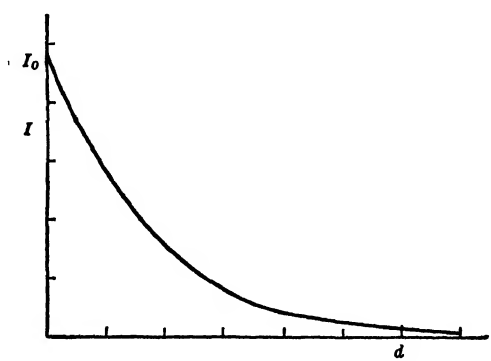


FIG. 8–2. Absorption of beta or gamma rays.

the rays produce after passing through the different thicknesses of absorbing material. The law is shown graphically in figure 8–2

and may be tested by plotting log $I$ against $d$ as in figure 8–3 since, from equation 8–1, we have

$$\log_\epsilon I = \log_\epsilon I_0 - \mu d \tag{8–2}$$

This is the equation of a straight line. The ordinates are values of $\log_\epsilon I$, the abscissæ are values of $d$, $\log_\epsilon I_0$ is the intercept on the ordinate and $\mu$ is the slope of the line, the negative sign indicating

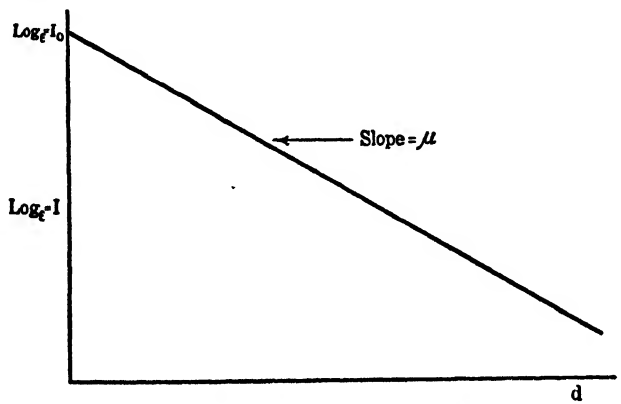


FIG. 8–3. To determine the absorption coefficient ($\mu$).

that the slope is downwards from left to right. From the last equation,

$$\mu = \frac{\log_\epsilon I_0 - \log_\epsilon I}{d} = \frac{\log_\epsilon (I_0/I)}{d} \tag{8–3}$$

so that this constant is defined as the logarithmic ratio of the intensities at two points distant one centimeter in the absorbing medium.

In the case of successive additions of layers of absorbing material, as described at the beginning of this chapter, one takes

$$I_1 = I_0\epsilon^{-\mu d_1} \qquad I_2 = I_0\epsilon^{-\mu d_2} \tag{8–4}$$

from which

$$\mu = \frac{1}{d_2 - d_1} \log_\epsilon \left(\frac{I_1}{I_2}\right) \tag{8–5}$$

$$\mu = \frac{2.303}{d} \log_{10} \left(\frac{I_1}{I_2}\right) \tag{8–6}$$

where $I_1$ is the intensity of the rays after passing through $d_1$ cm. of absorber, $I_2$ is the intensity after passing through $d_2$ cm., and 2.303 is used to change from the Naperian to the common system of logarithms. Thus, the intensity is measured before ($I_1$) and after ($I_2$) the addition of a sheet of the absorbing material of thickness $d\ (= d_2 - d_1)$.

The numerical value of $\mu$ for beta rays through aluminum varies from 13.1 to 5500. These correspond roughly to groups of high and low velocity respectively, but, in view of the irregularity of the paths of beta rays and their changes of velocity which sometimes occur rapidly and sometimes slowly, no definite correlation can be made. Even a single absorption coefficient is not a proof of the absolute homogeneity of the ray. The absorption curve is of the exponential form with most substances but in certain cases it must be considered in separate sections, each having a particular absorption coefficient. Radium C, for example, sends out beta rays having coefficients in aluminum of 13.2 and 53.

**The Absorption of X-rays.**

The absorption of a homogeneous beam of X-rays (consisting of radiation of but one wave-length) follows the exponential law of 8–1, which is repeated here.

$$I = I_0 \epsilon^{-\mu d} \qquad (8\text{–}1)$$

In this, $I$ is the intensity of the emergent beam, $I_0$ of the incident beam, $d$ is the thickness of the absorbing screen in centimeters and $\mu$ is the *linear absorption coefficient* of the screen material for that wave-length. The *mass absorption coefficient* is defined as the ratio $\mu/\rho$, where $\rho$ is the density of the absorbing medium which is used. The intensities may be measured by the ionization which they produce in a gas contained in a chamber. An electrode, sealed into the chamber with an insulating plug,* is charged to a sufficiently high potential to draw over all ions which are produced. These saturation currents, measured by an electrometer, give a

* The gases found most suitable in practice for this work are methyl iodide, methyl bromide and argon, in the order named. Fused quartz insulators should be used for sealing in the electrodes except with argon, where sulphur may be used.

direct measure of the X-ray beam. The intensity measurements may also be obtained from the blackening of a photographic plate. This method is full of uncertainties but gives moderately accurate values when the X-ray beams to be compared are of the same or nearly equal intensity and wave-length.

The general radiation from a gas-filled X-ray tube consists of a multitude of wave-lengths of different amplitudes. The maximum of these shifts toward shorter wave-lengths as the voltage of the tube is increased, as shown in figure 8–4. For a given voltage * there is a particular wave-length which may be taken as the mean value. Gas-filled tubes tend to operate on a fixed voltage determined by the gas pressure, regardless of the transformer or induction coil used, provided its potential is sufficiently high. This is

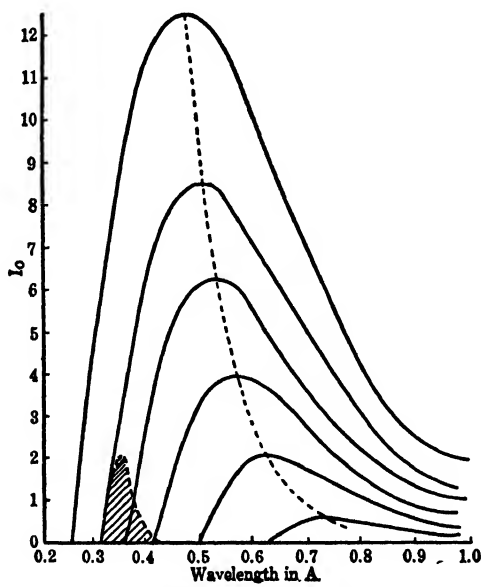


FIG. 8–4. The general radiation from a gas-filled X-ray tube at various voltages.

due to the change of current flow through the tube with change of potential. If the tube "hardens," i.e., its gas pressure decreases, the value of this fixed voltage rises and hence the wave-length

* See notes on technique at the end of this chapter.

decreases. However, for short exposures, the mean wave-length emitted by the tube may be taken as a constant. Further, the tubes are usually provided with a side tube containing some substance such as caustic potash which gives out a gas when heated. When the pressure in the tube becomes too low, the discharge shifts to this side arm, causing gas to be given out which raises the pressure to its normal operating value.

Two changes occur when the general radiation of an X-ray tube passes through an absorbing screen. Both the intensity and the mean wave-length decrease (only the harder rays penetrate to great depths). These changes occur in the emulsion of a photographic plate as well as in any intermediate absorbing screens. Hence, a monochromatic or one-wave-length beam of X-rays must be used in studying the absorption by different materials. Such a monochromatic beam may be obtained by the use of an X-ray spectrometer, just as a monochromatic beam of light is obtained by the use of a spectroscope. As a cruder but simpler method, one may use a filter in the path of the general radiation. A thin sheet of copper which reduces the original intensity of the beam to 10 per cent or less of its unfiltered value will serve in practice. The effect of such a copper filter is indicated in figure 8–4 by the shaded area. Using such a beam, it is still true that the mean wave-length emerging from an absorbing screen differs from that of the incident beam, but it is sufficiently close for practical purposes, particularly when the total intensity has been cut down to around one per cent of its original value. With the reduction in intensity the exposure time must be increased and the tube may undergo a slight hardening with consequent decrease in wave-length, but this also is small in practice.

The absorption of X-rays is due to two causes. First, the energy absorbed in the ejection of electrons (photo-electrons) from the atoms of the absorber, and second, the energy which is scattered in various directions (scattered X-rays). Thus,

$$\mu = \tau + \sigma \qquad (8\text{–}10)$$

where $\tau$ is the part due to the photo-electrons and $\sigma$ the part due to scattering. The latter is made up of the energy absorbed in the recoil electrons and in the energy change in the modified line of the Compton effect. In the X-ray region $\tau$, which is the de-

termining factor, is a function of the wave-length as follows,

$$\tau = K\lambda^3 \tag{8-11}$$

where $K$ is a constant. $\sigma$ becomes increasingly important at the shorter wave-lengths. As a first approximation for the short wave-lengths, including gamma rays,

$$\sigma = \frac{\sigma_0}{\left(1 + \frac{2h}{mc\lambda}\right)} \tag{8-12}$$

where $\sigma_0$ is a constant, $h$ is Planck's constant, $m$ the mass of an electron, $c$ the velocity and $\lambda$ the wave-length of the ray.

**The Absorption of Gamma Rays.**

Certain radioactive substances send out gamma rays having definite characteristic wave-lengths as observed by the crystal spectrograph. These wave-lengths are usually expressed in $X$ units ($1\ X$ unit $= 10^{-3}$ angstroms $= 10^{-11}$ cm.). For example, Radium B emits 21 lines ranging from 1365 to 793 $X$ units, the strongest being 1175 and 982. Radium B and C together emit 20 lines from 428 to 28 $X$ units, the strongest being 169, 159, and 99. Mesothorium emits two strong gamma rays, 168 and 145 and two weaker ones 62 and 52. The wave-lengths of many other gamma rays have been computed from the energy of the beta rays and from their absorption and scattering. These range from 269 for radium D to 4.7 $X$ units for thorium B and C together. Thus, the gamma rays extend from 1.365 to 0.0047 angstroms. The shorter the wave-length, the "harder" or more penetrating the ray and the smaller the absorption coefficient. The coefficient ($\mu$) for various gamma rays in aluminum ranges from 0.096 to 585 as shown by Table 8 at the end of this book.

**Absorption of Cosmic Rays.**

Repeated attempts to eliminate the natural leak of an electroscope have proven impossible despite the use of the most perfect insulators and the entire absence of ionizing radiations of known types. Lead shields several feet in thickness have been used to completely surround the instrument. These facts indicate that there exists an unusually penetrating radiation of feeble intensity.

From observations made in balloons at high and low elevations, and at various depths in lakes, various experimenters * have shown that they come from above the earth. Hence, they have been called *cosmic rays*. Their rate of absorption in water, as shown in figure 8–5, has given values of the absorption coefficients (in water)

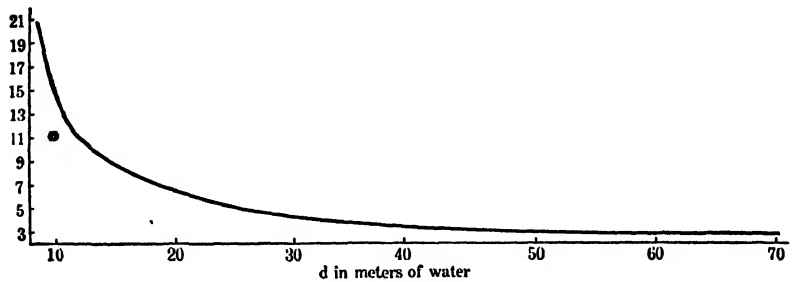


FIG. 8–5. The absorption of cosmic rays.

ranging from 0.04 for the more penetrating to 0.35 for the less penetrating. If equation 8–12 is valid for these isolated regions, the wave-lengths of cosmic rays are between 0.00008 and 0.00053 angstroms.

## EXPERIMENT 8–1

### ABSORPTION OF ALPHA, BETA AND GAMMA RAYS

*Apparatus.*

The apparatus consists of a gold leaf electroscope with its telescope, a radioactive preparation, radium E tubes, aluminum foils, aluminum sheets, lead sheets and a stop watch.

The radioactive preparation consists of a source which sends out alpha and beta rays, such as a sample of radium chloride which will give a fairly rapid fall of the leaf when placed in the electroscope. The radium E tubes serve as a source of beta and gamma rays. The aluminum foil may be of the kind often used for the leaves of an electroscope. The half dozen aluminum sheets should each have a thickness around 0.006 cm. and the three or four lead sheets should be around 3 mm.

* Hess, Kolhörster, Millikan and Cameron, etc.

*The Natural Leak of an Electroscope.*

When the electroscope has been properly cleaned with alcohol or ether and the brass surfaces sandpapered (if necessary) and left charged for at least half an hour, adjust the telescope so that only the edge of the leaf is sharply in focus. Use the same small irregularity on its edge as a reference mark in all work. Observe the natural leak by determining the time for the leaf to fall over a specified number of small divisions of the eyepiece with all ionizing agents removed. Call all these small divisions *one* division and always use it in the following. The reciprocal of the time to fall *one* division is then the natural leak. It should be so small that the leaf can hardly be seen to fall when observed through the telescope. It may be reduced, in a humid climate, by inserting a shallow dish of drying agent (calcium chloride will do) in the electroscope. It should be measured at the beginning and end of each part of the experiment and its average value subtracted from all readings. These corrected readings will henceforth be referred to simply as the rate of fall of the leaf or the activity of the rays.

*Relative Ionization of Alpha, Beta and Gamma Rays.*

Place the active preparation in the electroscope and measure the ionization current (the activity) due to the alpha and beta rays together. Place a sheet of aluminum some 0.006 cm. thick over the active material and measure that due to the beta rays alone, taking care that the sheet is not contaminated by direct contact with the active substance. Place a sheet of lead about 3 mm. thick over the substance and make sure there are no appreciable gamma radiations, i.e., the fall of the leaf is the same as the natural leak.* Deduce the relative ionization of the alpha and beta rays.

Now, using the stronger source (the radium E tubes), cut off all alpha rays and observe the intensity of the beta and gamma rays. Then with the lead absorber obtain that of the gamma rays alone. Deduce the ratio of the beta to gamma activities.

* If it is not, the gamma activity as well as the natural leak must be subtracted from the two readings.

*Absorption of Alpha Rays by Aluminum.*

Observe the ionization obtained as the alpha rays are cut off by successive layers of thin aluminum foil.* The foil is difficult to handle unless mounted between two cardboard sheets through which large holes have been cut. A series of such absorbing screens may be made up, containing 1, 2, 4, 8, 12 and 16 foils, whose combinations give the desired thicknesses. Care should be taken that these foils do not come in direct contact with the active material. Plot a curve of the activities as ordinates and the number of foils used as abscissæ.

*Absorption of Beta Rays.*

Cut off all the alpha rays and measure the absorption of the beta rays using the sheets of aluminum. Plot as with the alpha rays. Also plot logarithms (to the Naperian base †) of the activities vs. total thicknesses of the absorbing screens. The slope of the line is the coefficient of absorption of these beta rays in aluminum. Compare with the accepted value.‡

*Absorption of Gamma Rays.*

If the intensity of the radium E tubes is sufficiently great, measure the absorption of the gamma rays using various thicknesses of lead and deduce the absorption coefficient.

## EXPERIMENT 8-2

### THE ABSORPTION AND WAVE-LENGTH OF X-RAYS

The purpose of this experiment is to determine the mass absorption coefficients of various substances and the wave-lengths of the X-rays which have passed through these materials.§

* Cigarette papers have been found of sufficiently uniform thickness and are much easier to handle than the aluminum foil.

† Common logarithms may be used. Then the slope is 0.4343 times the absorption coefficient.

‡ Equation 8-6 may be used instead of the graphical method. Take an average of the coefficients computed for various thicknesses.

§ More precise measurements may be obtained using the hot filament X-ray tubes and a crystal spectrograph to isolate one wave-length of the beam.

The general radiation from a gas-filled X-ray tube is to be filtered with a copper screen, passed through several step-like absorbing materials and recorded on a photographic plate. The arrangement of the apparatus is shown in figure 8–6 where the X-ray tube is located in a box *L* made of sheet lead approximately one-eighth inch thick. The spark coil *A* used to operate the tube may be such as to give a spark between needle points about two inches long when the tube is being used. A hole four or five inches on a side is cut in the box to allow the X-rays to pass through to a copper filter *F*. For a tube whose mean wave-length is around 0.3 angstroms, this should be about 0.05 cm. thick. The approximately homogeneous rays which emerge from this filter pass through the absorbing materials at *S* to a photographic plate *P*. The plate should be about six inches from the screens to avoid scattered radiation. Details of the absorbing screen may be seen in figure 8–7 and a drawing of the photographic record in figure 8–8.

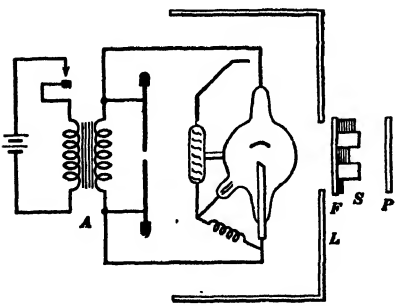


FIG. 8–6. Apparatus for measuring the absorption and wave-length of X-rays.

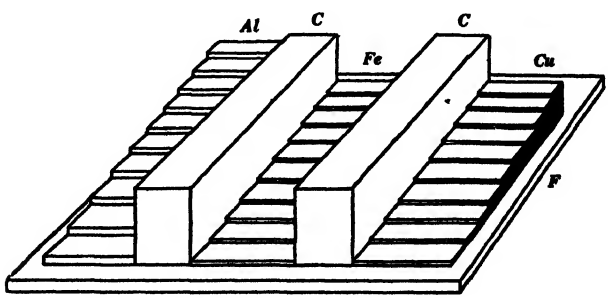


FIG. 8–7. X-ray absorption "screen" and filter.

The graphite blocks *C* are about 1.2 cm. thick. Each of the aluminum, iron and copper steps is approximately 0.06, 0.005 and 0.005 cm. thick, respectively.

With proper exposure time (say one and one-half hours, using

duplitized X-ray films) and development, the blackening back of the graphite lies between the extremes of light and dark for the

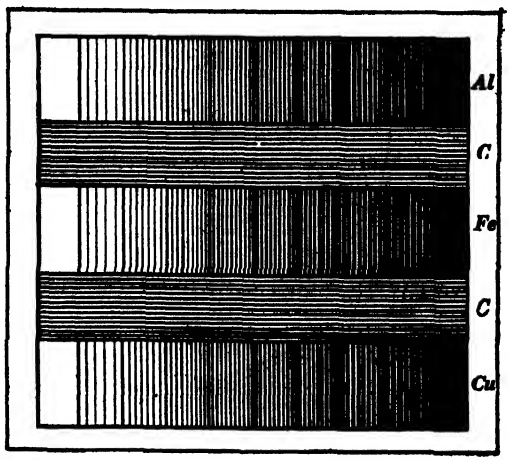


FIG. 8–8. The photographic record.

other substances. A certain step may possibly be found by eye for which the blackening is the same as that back of the graphite. If the coincidence is not exact, the thicknesses which give equal blackening may be determined by photometer measurements. The intensities of the X-rays reaching the plate then being equal, we may write

$$I = I_0 \epsilon^{-\mu_m \rho_m d_m} = I_0 \epsilon^{-\mu_c \rho_c d_c}$$

from which

$$\mu_m = \mu_c \frac{\rho_c}{\rho_m} \frac{d_c}{d_m} \qquad (8\text{–}13)$$

where $d_m$ is the thickness in centimeters of the aluminum, iron or copper, as the case may be, which allows the same intensity of X-ray beam to pass through as $d_c$ centimeters of graphite. $\rho_m$ is the density of the aluminum, iron or copper, and $\rho_c$ is that of graphite. The $\mu$'s are mass absorption coefficients.

The mass absorption coefficient $\mu_c$ for graphite (which is the same for any form of carbon) is to be taken as the standard. This is chosen since its value does not change with wave-length as much as other substances. (See Table 9 at the end of the book.) Inasmuch as the wave-length emitted by the tube is unknown, the

correct value of $\mu_c$ cannot be obtained at first. Let us assume that the wave-length is around 0.5 angstroms. Then the value of $\mu_c$ may be taken as 0.30. Substituting this and the other quantities in equation 8–13 gives an approximate value of $\mu_m$. Say $\mu_m$ for copper was thus found to be 5.19. This corresponds to a wave-length of 0.316 angstroms as seen from the table or, better, from a graph plotted from this data. The process is now to be repeated, i.e., $\mu_c$ at 0.316 angstroms is equal to 0.203. Using 0.203 instead of 0.3 in equation 8–13 gives the mass absorption coefficient of copper as 3.51 which, from the table, corresponds to a wave-length of 0.278 angstroms. The process is then repeated again. If, for the average tube, the value of $\mu_c$ is taken as 0.20, the steps need be repeated but once.

This method of successive approximations is to be repeated for the other absorbing materials. It is not to be expected that the wave-lengths so determined will all be exactly the same since the X-ray beam is not strictly monochromatic but the values should be less for those substances having greater absorption coefficients.

## NOTES ON TECHNIQUE

Step-down transformers for heating the filaments of the rectifying tubes such as used with X-ray tubes may be constructed in the following manner. Secure ten strips of a good grade of transformer iron, each one and one-half inches wide, one-sixteenth inch thick and eight feet long. Bend these into a circular core whose inside radius is about one foot. Wind with two layers of friction tape for insulation. This must bind tightly or the transformer will hum badly. Around this ring wind a layer, 300 turns, of number 18 D.C.C. wire. This is the primary and is connected through a 48 ohm, 3.2 ampere rheostat to the 110 volt A.C. supply. The secondary coil, which passes through the primary ring with approximately one-foot spacing at all points, is made of 50 turns of number 14 D.C.C. wire (radius one foot) with taps every fifth turn after the thirty-fifth turn. No iron is used in the secondary, the ring being held together with friction tape. The secondary

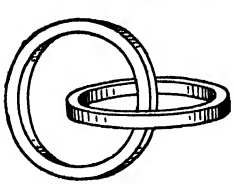

FIG. 8–9. Filament transformer for high tension lines.

potential will be 6 to 15 volts. Support the two coils with paraffined wood.

The measurement of high voltages may be made with a spark gap in parallel with the induction coil or transformer. Values of voltages for various sparking distances are given in Table 2. Another method is to connect a large and a small condenser in series with each other, across the line. From the relation $Q = CV$, it may be seen that the majority of the potential drop takes place across the small condenser. Hence the drop across the large condenser may be measured with an ordinary high resistance voltmeter and the total voltage calculated from the known values of the capacities.

Another method consists in measuring the potential drop across a portion of a very high resistance connected across the line. Such high resistances may be made up of tubes of various liquids. Alcohol (any form) may be added to xylol to lower its resistance to the desired high value, say 100,000 ohms per cc. The glass tubing containing this solution should have a sufficiently large cross section to prevent overheating with the power used. Polarization at the electrodes causes changes in the resistance and hence in the calculated voltages. The following solution (Pohl and Pringsheim; Ver. der D. Phy. Ges. 15, p. 175, 1913) has a constant resistance at various temperatures: 121 gr. manite, 41 gr. boric acid, 0.06 gr. KCl, 1 liter water. Amalgamated zinc electrodes in a solution of saturated zinc sulphate give non-polarizable electrodes. (See figure 8–10.) Cadmium iodide in amyl alcohol, using amalgamated cadmium electrodes, is also very satisfactory for such high resistances. (One meter length, 1 mm. diameter gives approximately 100 megohms.)

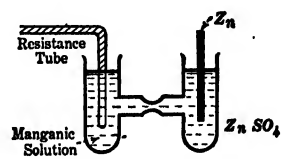


FIG. 8–10. Non-polarizing electrode for high resistances.

Extremely high resistances may be obtained by using a stream of water which breaks up into drops. For lower resistances, use ordinary water in a long tube. For large power, the water should be circulated. Seventy-five feet of three-eighths inch tubing full of water has a resistance of about 15 megohms. Such resistances in series with an oscillograph allow the study of the wave form of high potentials.

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# CHAPTER 9

## RADIOACTIVE SUBSTANCES

**Introduction.**

A given sample of radioactive substance sends out a definite number of alpha, beta or gamma rays. The number of ions which these can produce in air or other gas at a fixed temperature and pressure is directly proportional to the number of alpha, beta or gamma rays. If saturation voltages are applied across the gas, all ions produced will be drawn out. Hence, the ionization current is directly related to the number of grams of radioactive substance. For example, one gram of radium emits $3.45 \times 10^{10}$ alpha particles per second, each of which produces roughly $1.74 \times 10^{5}$ ions, whose individual charges are $4.77 \times 10^{-10}$ e.s.u. If all of these be drawn over to the plates of an ionization chamber, the resulting current will be $9.26 \times 10^{-4}$ amperes. In an electroscope, whose case acts as one plate of an ionization chamber, its leaf as the other plate, ions will be drawn to the leaf, neutralizing its charge and causing it to fall at a rate proportional to the amount of active substance causing the ionization. Thus the "intensity" of a radioactive substance can be measured, i.e., the amount remaining after part has disintegrated, can be determined.

The unit of radioactivity, called the *curie*, after Madame Curie, is based on the mass of an active substance. As defined by the Radiology Congress in Brussels in 1910, the curie is "The amount of emanation in equilibrium with one gram of pure radium." This occupies 0.61 cubic millimeters (76 cm., 0° C.) and has a mass of $6.04 \times 10^{-6}$ grams. The International radium standard consists of 21.99 milligrams of specially purified radium chloride prepared by Mme. Curie and preserved at the Bureau International des Poids et Mesures at Sèvres near Paris, France.

Another unit of radioactive intensity sometimes used is called the Mache unit and is based on ionization currents. It is defined as "one thousand times the saturation current due to one curie of emanation without disintegration products when all the radiation

is absorbed in the air of the ionizing chamber." One Mache unit is equal to $3.64 \times 10^{-10}$ curies.

Secondary standards have been prepared and distributed throughout the various countries. In order to determine the activity of a given substance, it is only necessary to compare the rates of fall of the leaf of an electroscope in which the unknown and standard have been placed in succession. Certain necessary precautions will be discussed later.

**Radioactive Transformations.**

To illustrate the transformation of one radioactive substance into another, a particular case will be given where uranium I changes into uranium $X_1$. Uranium I, with an atomic weight of 238 and an atomic number of 92, is the heaviest element known and is found at the end of the Periodic Table. As it emits alpha rays, it slowly changes into uranium $X_1$ so that the two are always found together. Uranium $X_1$ is continually emitting beta and gamma rays, changing into another element. Hence, if the mixture is placed in a beta ray electroscope, a constant activity is shown, the uranium $X_1$ decaying at the same rate as it is being formed. This is known as *stable radioactive equilibrium*. The two may be separated from each other by chemical means * and placed in different beta ray electroscopes. Their activity curves are shown in figure 9–1. Curve *A* shows the beta ray activity in the uranium I sample and hence shows the formation of uranium $X_1$ (since uranium I does not emit beta rays). Curve *B* shows the decay of the isolated uranium $X_1$. In order to show that this is the decay curve of uranium $X_1$ and

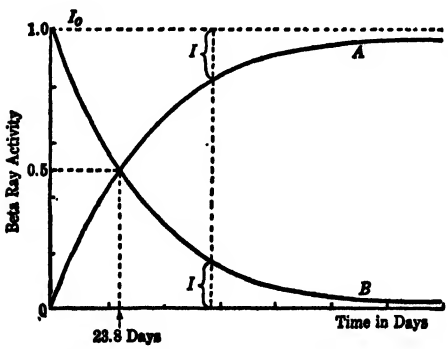



FIG. 9–1. Formation and decay of uranium $X_1$.

* An aqueous solution of uranium nitrate in ammonium carbonate yields a precipitate which may be redissolved. A new precipitate is formed which is uranium $X_1$ alone.

not of its disintegration products, the following series is given.

$$\underset{4.67 \times 10^9 \text{ years}}{\mathrm{UI}} \xrightarrow{\alpha} \underset{24.6 \text{ days}}{\mathrm{UX_1}} \xrightarrow{\beta, \gamma} \underset{1.15 \text{ minutes}}{\mathrm{UX_2}} \xrightarrow{\beta, \gamma} \underset{2 \times 10^6 \text{ years}}{\mathrm{UII}} \xrightarrow{\alpha}$$

The figures which are given are the times for half of the substance to decay. It is to be noted that neither uranium I or II contribute to the activity as they emit only alpha particles and a beta ray electroscope is used. The beta rays of uranium $X_2$ constitute the major activity of the curve *B* of figure 9–1 but, since this substance decays quickly, it is its continual replenishment by uranium $X_1$ which determines the shape of the curve, i.e., the shape of *B* is determined by uranium $X_1$, although it is actually due to uranium $X_2$. The fact that a decay curve follows the activity of a long-life substance in spite of the presence of its short-lived products is a general principle in this subject.

**Rutherford-Soddy Theory of Transformations.**

It is assumed that the number of atoms which break up each second is a constant fraction of those present at any given instant. For example, if there are 10,000 atoms at the start and 200 (2 %) break up during the first second, sending out an alpha or beta and gamma ray, then during the next second 2 per cent (196) of the remaining 9800 atoms will break up and during the third second 2 per cent of the remaining atoms break up, i.e., 192 of the 9604 will disintegrate, etc. The ratio of the number which break up each second to the total number is called the *transformation constant* and is designated by $\lambda$. Then

$$n = \lambda N \tag{9–1}$$

where *N* is the total number present at a certain time and *n* is the number which break up at that time during one second. We then have

$$\frac{dN}{dt} = -\lambda N \tag{9–2}$$

the negative sign indicating a decrease in the number of unchanged atoms. From this

$$\int \frac{dN}{N} = \int -\lambda dt$$

$$\log_e N = -\lambda t + C$$

and when $t = 0$ $\quad \log N_0 = C$

giving $\quad \log \frac{N}{N_0} = -\lambda t$

$$N = N_0 \epsilon^{-\lambda t} \tag{9–3}$$

where $\epsilon$ is the base of the Naperian system of logarithms. This exponential equation gives the number of atoms $N$ existing after a time $t$ when there were $N_0$ atoms at the start. Substituting this equation in (9–1) gives

$$n = (\lambda N_0)\epsilon^{-\lambda t} = n_0 \epsilon^{-\lambda t} \tag{9–4}$$

which is the number of atoms $n$ breaking up each second after a time $t$ seconds, while $n_0$ is the number disintegrating each second at the start. It is now assumed that the number of particles emitted each second is the same as the number of atoms breaking up. It has been shown that saturation ionization currents are proportional to the number of particles emitted. Hence equation (9–4) may be written

$$I = I_0 \epsilon^{-\lambda t} \tag{9–5}$$

where $I$ is the intensity of a radioactive substance $t$ seconds after it had an intensity $I_0$ and $\lambda$ is the transformation constant. This is the equation of curve $B$, figure 9–1, as has been tested experimentally many times. Curves $A$ and $B$ being similar, but inverted, the equation of the former is

$$I' = I_0 - I = I_0(1 - \epsilon^{-\lambda t}) \tag{9–6}$$

which has also been verified experimentally.

**Radioactive Series.**

In general, the transformations are not so simple as the one used for illustration, as several decay products of a parent substance may be present at the same time, emitting radiations of such kind and having such duration of life as to mask each other. The total activity may decrease, increase or remain constant. From a study of the activity curves and other data, the continuous decay from the heavier to the lighter elements has been traced out. These *radioactive series* are given in figure 9–2 and in Table 10 at the end

of the book. It will be seen that they all start from two parent substances, uranium I and thorium. The exact element from

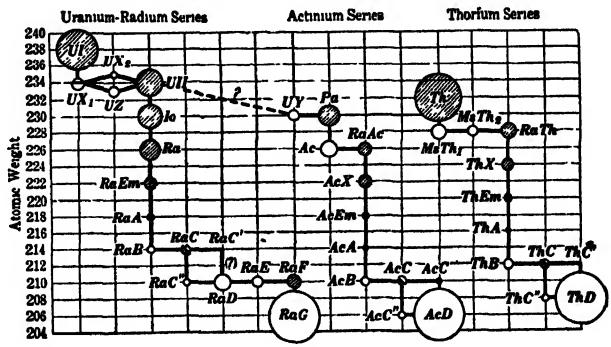



FIG. 9–2. The radioactive series.

which the actinium series branches off from the uranium series is as yet unknown.

**Radioactive Constants.**

The transformation constant of a given substance may be determined by plotting the data used for curve *B*, figure 9–1, in a different manner. If the ordinates are $\log_\epsilon I$ and the abscissæ the time, a straight curve will result whose negative slope is $\lambda$, the transformation constant.

The *mean or average life* ($L$) of a radioactive substance is defined by the relation,

$$L = \frac{1}{\lambda} \tag{9–7}$$

Substituting this time for $t$ in the transformation law gives $N/N_0 = 1/\epsilon$. In other words, during the average life of a substance $1/2.718+$ of it will disintegrate.

The third constant is the one most widely used and is called the half life period or *half life* ($T$). It is the number of seconds for the activity to fall to half its original value, i.e., for half the atoms to break up. Then $N/N_0 = \frac{1}{2} = \epsilon^{-\lambda t}$; $-\log_\epsilon 2 = -\lambda T$, whence

$$T = \frac{0.693}{\lambda} = 0.693L \tag{9–8}$$

These constants are characteristic of a given radioactive substance and allow its identification equally as well as the range of its alpha particles or chemical analysis. They may be measured directly if the substance can be isolated from its parent and products, or they may be deduced from complicated activity curves.

Substances may be isolated chemically by precipitation, electrochemical deposition or by fractional crystallization. They may also be separated by volatilization, since different substances have different volatilization points, or by electrolysis. The method of *recoil* makes use of the fact that as an alpha particle leaves its atom the remainder of the substance recoils backwards. Thus, if thorium C, radium A or actinium C be placed between positive and negative metal plates, the recoil thorium D, radium B or actinium D will collect on the negative plate. From considerations of the momenta involved, the velocity of the alpha particle may be computed. From radium A, this amounts to $3.16 \times 10^7$ cm. per second. Gases may be freed from their parents by bubbling air through a solution containing them, or by boiling the solution. In the ignition method for radium emanation from radium, the radium salt is mixed with an appropriate flux, such as sodium acid phosphate, and sealed in a glass tube. Within 7.7 days, 75 per cent of the total equilibrium amount of gas will be formed and in 3 weeks there will be 99 per cent. The tube is then connected to an emanation electroscope and heated to drive out the emanation.

The constants may also be computed from measurements on the range of alpha particles, using the law expressed in figure 7–13 and given in equation 7–6, although the results are not very accurate. The transformation constant is obtained if the number of alpha particles emitted per gram each second, observed with a fluorescent screen or Geiger counter, is divided by the number of atoms per gram of the substance. The number of atoms per gram is given by dividing Avogadro's number ($6.06 \times 10^{23}$) by the molecular weight.

Several methods have been used for short-lived products, one of which is illustrated in figure 9–3. Air is drawn through a metal tube and carries the emanation (a gas) from the active substance (*XX*), say actinium X, along the negatively charged wire

where it leaves an active deposit. During the time the gas is passing the length of the wire, it has practically all decayed. Hence the amount of active deposit (having comparatively long

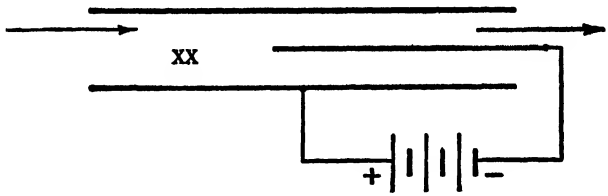



FIG. 9–3. Decay rate of short-lived substances.

life) at the front end of the wire is greater than that near the end of the tube. The wire is removed and cut into pieces, each of which is tested with an electroscope. From these activities and the rate of flow of the gas, the rate of decay is obtained. In this way the half period of actinium emanation was found to be 3.92 seconds.

For weak substances having very long periods, the transformation constant may be obtained by measuring the intensity of it and its product combined when a stable condition of equilibrium exists between them, i.e., the number of atoms of the parent which break up each second (also equal to the number of atoms of the product formed each second) is equal to the number of atoms of the product which break up each second.

Then

$$\lambda_1 P = \lambda_2 Q$$

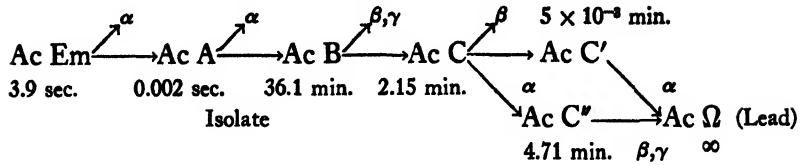
$$\lambda_1 = \lambda_2 \frac{Q}{P} \qquad (9\text{–}9)$$

The transformation constant $\lambda_2$ of the product and the equilibrium ratio $Q/P$ of product to parent (grams/grams) must be known from previous determinations.

**Active Deposits — The Parent Substance Transforms Rapidly.**

In the case of a slowly changing parent, the rate of production of its first product is essentially a constant but, when it transforms rapidly, the new substance is formed in smaller and smaller amounts as time goes on. This is illustrated by the alpha ray activity of

actinium C produced by actinium B in the series




as shown in figure 9–4. Actinium B was chemically isolated and then placed in an alpha ray electroscope. From the series, it is seen that actinium B and C″ emit only beta and gamma rays and hence do not contribute to the curve. Further, it is seen that actinium C′ decays in a much shorter time than C, so that the observed effects are those of C alone. With a parent of long life, the curve would rise to a maximum and remain constant as *OMN* in the figure. But B is decaying at a moderate rate so the activity drops to *W* as time goes on. The half period of B can be obtained from the curve *MW*. The rapid rise *OM* is due to the fact that actinium C is being formed at a greater rate than it is decaying. These two rates are equal at *M* and a condition of *transient equilibrium* exists.

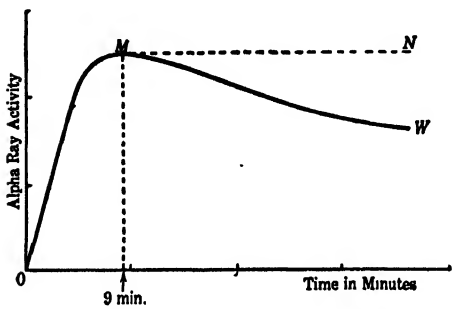
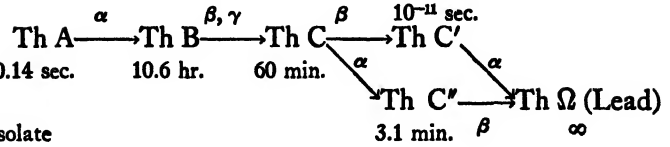



FIG. 9–4. Activity curve of a substance having a short-lived parent.

As a second illustration of the case where the parent transforms very rapidly, we may take the active deposit of radium. On decaying, radium produces a gas called radium emanation or radon. This, in turn, decays into radium A, as a solid deposit on the walls of the containing vessel. This, in turn, changes into radium B, then C, C′ and C″. A, B, C, C′ and C″ form the *short life active deposit*. They are followed by D, E and F (Polonium), which constitute the *long life active deposit*. F changes into lead which undergoes no further changes as far as we can tell.

In similar fashion the active deposit of thorium is given by the series.




After isolation, thorium A changes very rapidly into thorium B. Placed in an alpha ray electroscope, the activity curve shows the combined formation and decay of thorium C from B since the only other emitter of alpha rays is C′ whose half period is so short as not to mask the activity of C. The resulting curve is similar to that of figure 9–4 except that the maximum is not reached until after 10.6 hours.

**Radioactive Displacement Laws and Isotopes.**

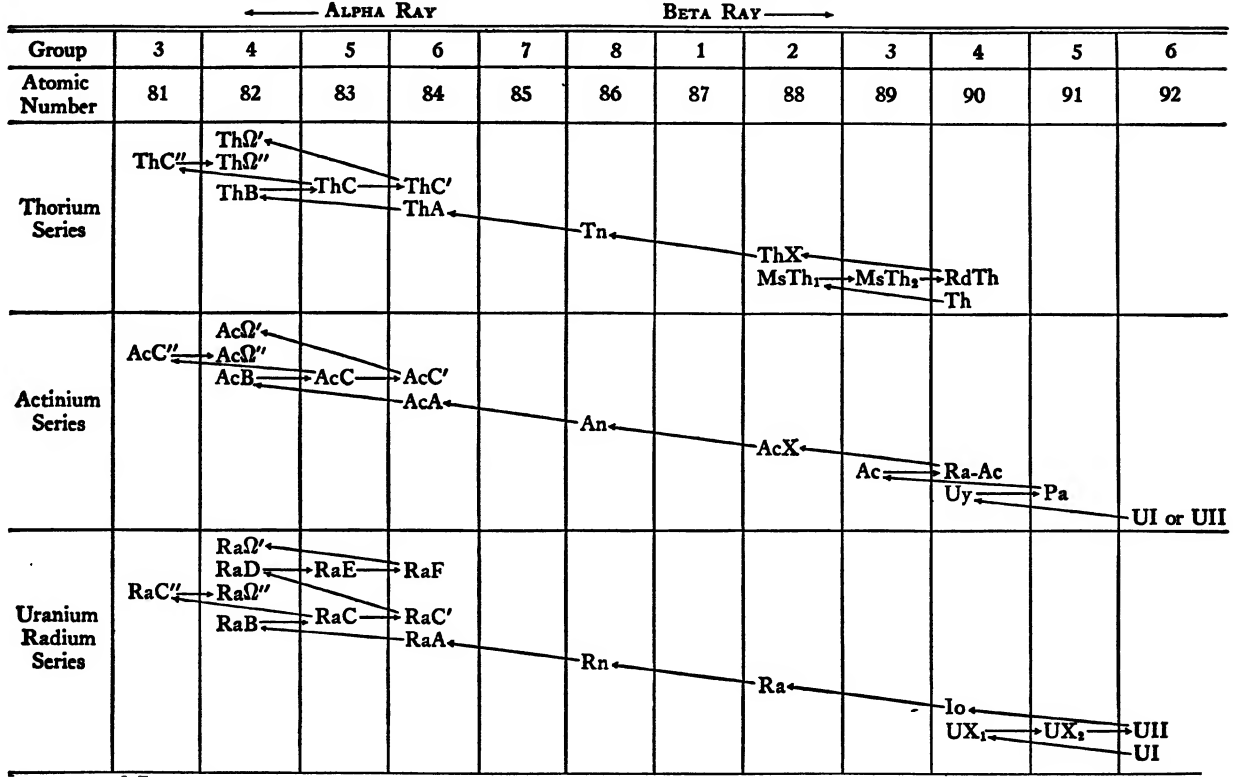
Radium, of atomic weight 226, emits an alpha particle of atomic weight 4 and becomes radium emanation of atomic weight 222. With the emission of an alpha particle, the nuclear charge and its equivalent, the atomic number, decrease by two, changing from 88 to 86. That is to say, the chemical properties of radium and its emanation are different. Radium, in turn, emits an alpha particle and becomes radium A with atomic weight 218 (less by 4) and atomic number 84 (less by 2). In general: *For any alpha ray transformation, the new element has an atomic weight less by four units and an atomic number less by two units than its parent.*

Radium B emits a beta particle and becomes radium C. The beta particles are electrons having a mass negligible in comparison to the nuclear mass. Hence, no essential difference exists between the atomic weights (214) of radium B and C. But the chemical and physical properties of these two are different since the nuclear charge has increased positively by an amount equal to one electron. Thus, the atomic number of radium B is 82 while that of radium C is 83. In general: *For any beta ray transformation, the new element has the same atomic weight as its parent but an atomic number greater by one.*

Following these *displacement laws*, the location of any radioactive element in the periodic table can be determined. The accompanying table of radioactive elements shows such an arrangement.

Those elements in the same vertical column have the same

## POSITIONS OF THE RADIOACTIVE ELEMENTS IN THE PERIODIC TABLE.



atomic number although their atomic weights differ, which means that they have the same chemical and physical properties except atomic weight. They are thus grouped together at the same place in the periodic table. In other words, all elements in a vertical column of the table are isotopes and, when once mixed together, cannot be completely separated by any chemical or physical means known today.

## EXPERIMENT 9-1

### THE INTENSITY OF RADIOACTIVE SUBSTANCES

An alpha ray electroscope is to be used. Its natural leak is determined and subtracted from all subsequent readings. (See experiment 8–1). The rate of fall of the leaf, i.e., the reciprocal of the number of seconds for the leaf to pass over a fixed distance of the scale in the telescope, is proportional to the intensity of the radioactive substance placed in the instrument. Always use the same divisions of the scale in comparing the intensity of various substances.

It will be found convenient to charge the electroscope beyond the desired scale position and then lower it to this point by removing small amounts of the charge by rubbing the leaf support with a small piece of paper. If a standard radioactive substance is at hand, the activity of an unknown substance can be obtained by comparison.

The active material, in a shallow metal tray, is placed in the electroscope, as in figure 8–1. Since the alpha rays are easily absorbed, only the surface layers contribute to the activity and the thickness of the material in the pan is unimportant unless the layer is very thin. However, some of the activity is due to beta rays which are not so easily absorbed in passing through the material itself. Therefore, use equal weights, or roughly, use equal thicknesses (1 mm.) of the various materials (spread evenly in shallow metal pans about 6 cm. in diameter).

The amount of the ionization current set up by a given material is given in e.s.u. by $i = Q/t_1 = (C\,\Delta V)t_1$ where $C$ is the capacity of the leaf system of the electroscope (in e.s.u.) and $\Delta V$ is the drop of potential (in e.s.u.) corresponding to the movement of the leaf over a definite number of divisions of the observing telescope in

$t_1$ seconds. $\Delta V$ may be obtained by connecting the leaf to a battery of known voltage or to the needle of a Braun (or other) electrostatic voltmeter, when the change of volts per scale division is obtained. Divide volts by 300 to get e.s.u.

The capacity $C$ of the leaf system is found by adding a small standard condenser in parallel with it, as the dotted lines of figure E–1, and observing the time $t_2$ (seconds) for the leaf to pass over the same divisions as before, the active material still being present. Then

$$C = C_0 \frac{t_1}{t_2 - t_1} \tag{9–10}$$

in which $C_0$ is the added capacity. This may consist of two concentric cylinders. If they are of length $l$ cm., the capacity $C_0$ is given in e.s.u. by

$$C_0 = \frac{Kl}{2 \log_e (b/a)} \tag{9–11}$$

$K$ for air is equal to unity, $b$ is the inside radius of the outer cylinder and $a$ is the outside radius of the inner cylinder. Since these cylinders are of nearly the same radius, it is important that they be as nearly concentric as possible.

The number of ions produced per second equals the number drawn to the leaf each second and this is equal to the ionization current $i$ divided by the charge on each ion ($e = 4.77 \times 10^{-10}$ e.s.u.). If $A$ is the area in square centimeters of the active material, then the number of ions produced per second per square centimeter is

$$n = \frac{i}{Ae} \tag{9–12}$$

*Experiment.* — Compare the intensities of at least three substances such as uranium oxide, pitchblende, thorium nitrate, etc., taking the average of four determinations for each. If a *standard* is available, express the activities in milligrams of radium; if not, express in terms of one of them, say the pitchblende.

Measure the capacity of the leaf system using the equation above and compute the ionization current in amperes produced by the standard substance. Also compute the number of ions which it produces per second per square centimeter.

### EXPERIMENT 9-2

### RATE OF FORMATION OF THORIUM C

An alpha ray electroscope is to be used. Its natural leak is determined and subtracted from all subsequent readings. Determine the natural leak of the electroscope before and after the experiment and use its average value. (See experiment 8–1.) The rate of fall of the leaf, i.e., the reciprocal of the number of seconds for the leaf to pass over a given number of divisions of the scale in the telescope, is proportional to the activity of the substance as it is being formed. Always use the same divisions of the scale in the following.

Figure 9–5 shows the apparatus for obtaining the active deposits

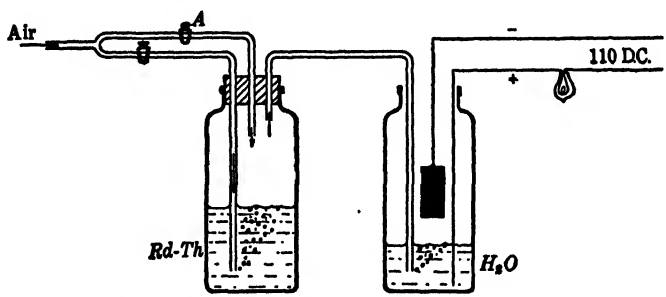



FIG. 9–5. Preparation of the active deposit of thorium.

of thorium. Air is bubbled gently through a solution of radiothorium (Rd-Th). Violent bubbling is prevented by diverting part of the compressed air through the stop cock *A*. The mixture of air and thorium emanation freed from the solution is bubbled through water to remove traces of the solution. A negatively-charged nickel plate will collect an active deposit if placed in this gas. Since the emanation is allowed to escape freely into the air above the water this process must not be carried on in the room used for any radioactive measurements. Otherwise the natural leak of the instruments will be found to be very great.

Expose the plate in this fashion for about five minutes, then place it quickly in the alpha ray electroscope and observe the rate of fall of the leaf at regular intervals for about two hours. Plot the activities as ordinates and time as abscissæ, using values of time

taken at the middle of the time interval required for the determination of the corresponding activities. This curve will show the formation of thorium C.

If continued over a long period of time, such a curve as shown by the solid line of figure 9–4 will be obtained. From the decay part of this curve the half period of thorium B may be deduced.

### EXPERIMENT 9–3

### RATE OF DECAY OF THORIUM C

The apparatus and technique used in this experiment is the same as in the preceding one. A negatively charged platinum plate is exposed to thorium emanation for about two hours. This permits the accumulation of a considerable amount of thorium B and C. Rinse the plate gently in alcohol to remove traces of thorium emanation and then place in concentrated hydrochloric acid. This dissolves the active deposit. Now, dilute with water, insert a nickel plate and stir it around for a short time (about a minute). Thorium C *alone* will be electrochemically deposited on the nickel plate. Wash gently in hot water and quickly transfer to an alpha ray electroscope. Plot the decreasing activities as ordinates and times as abscissæ. From this decay curve determine the half life of thorium C.

### EXPERIMENT 9–4

### DECAY OF THORIUM EMANATION

Charge an emanation electroscope, figure E–9, and observe the natural leak. If it is too large, the chamber must be opened, sandpapered and cleaned with alcohol or ether to remove active deposits. Partially evacuate the chamber, charge the leaf and then introduce a small amount of thorium emanation, stopping as soon as the leaf begins to fall rapidly. Since the half life of thorium emanation is comparatively short, observations of the activity must be made quickly. Observe the time of fall over a small number of divisions, allowing the leaf to continue for a second observation at a different part of the scale. The relative current changes for the various parts of the scale may be found by observing the time required to pass over the specified divisions with a constant source of ionization.

Plot a curve showing the decay of the emanation with time and deduce the half period of the thorium emanation.

### EXPERIMENT 9-5

### DECAY OF RADON

An emanation electroscope is used as in the preceding experiment but the decay rate of radon (radium emanation) is slower than that for thorium emanation so that the activities at various times may be determined more leisurely.

Seal some uranium ore, such as carnotite, with an equal amount of sodium acid phosphate, in a long glass tube. Glass wool plugs are used to keep the material in place. The ends of the tube are drawn down to points when sealing off. The radon is allowed to accumulate for about two weeks. A rubber tube is then slipped over one end of the tube and connected to the partially evacuated electroscope chamber. When ready to take the readings, heat the tube, starting at its middle and working the flame both ways. While this is being done, break the end of the tube inside the rubber tubing and open the stop cock to the chamber. Then break the far end of the glass tube so that air will sweep through the tube. Finally close the stop cock. The chamber then contains the radon.

Plot the activity curve from observations made at intervals of several hours and deduce the half period of radon.

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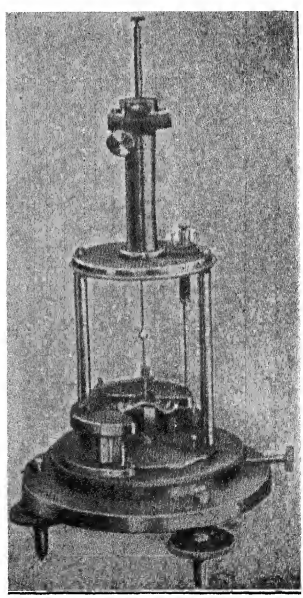
# APPENDIX A

## ELECTROMETERS

**Principle and Use of the Quadrant Electrometer.**

This instrument is used to measure currents and voltages. It operates on the principle of electrostatic repulsion. Essentially, there are three parts: two fixed conductors, called the quadrants, and a suspended conductor, called the needle. As ordinarily used, the needle is charged to a high fixed potential (100 volts) and a difference of potential is applied between the quadrants. The needle is attracted toward one of the quadrants and repelled by the other. The rate at which the needle moves is a measure of the current and the final deflection is a measure of the difference of potential between the quadrants.

The quadrant electrometer is generally used to measure currents ranging from about $10^{-8}$ ampere (the usual limit of the ordinary wall type galvanometer) to $10^{-15}$ or $10^{-16}$ of an ampere, (such as produced in a gas by the action of radioactive substances, X-rays or ultra-violet light). It can be adapted for measurements of larger currents but is not as convenient as the galvanometer or ammeter. It will measure potential differences from $10^{-5}$ to 10 volts and, in the special Kelvin form, it will measure many thousand volts, A.C. or D.C.



*Courtesy Cambridge Scientific Instrument Co.*

FIG. A–1. The Dolezalek electrometer.

**Description of the Instrument.**

The Dolezalek is the most common of the many forms of electrometers (figures A–1 and A–2). The needle is made of aluminum, flat

and figure-eight-shaped, suspended by a phosphor bronze or platinized quartz fiber between the quadrants. The quadrants consist of a pill-box-shaped brass chamber split into four parts. Opposite quadrants are connected together with wires, each pair serving as one fixed conductor. The needle and quadrants are supported with amber or quartz since great care must be taken with extremely small currents to minimize any leak of the electricity. The apparatus is surrounded by a grounded metal case, not shown in the figure, which cuts off air currents and stray electrostatic effects or charges. The rotation of the needle is observed with a scale and a telescope focused on a small mirror fastened to the suspension.

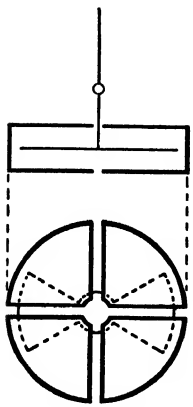


FIG. A–2. The Dolezalek electrometer.

**Electrometer Connections.**

Figure A–3 shows the *heterostatic* connection for use in measuring the voltage *v*. The needle *N* is kept at a high potential (30 to 160 volts) by the battery *V*. One pair of quadrants is grounded and the other is raised to the potential (*v*) which is to be measured. A protective resistance *P* of large value (lavite, 48,000 ohms) must be used to prevent burning out the battery and suspension in case the needle should accidentally touch one of the quadrants. The ground *G* (such as a water pipe) serves to prevent surrounding objects from inducing charges and may be made at any point in the connections, provided the entire apparatus is carefully shielded.

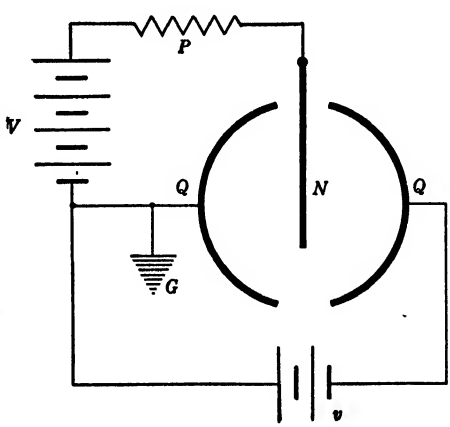



FIG. A–3. "Heterostatic" voltage connection of an electrometer.

. Figure A–4 shows the *idiostatic* connection for measuring the voltage $v$. Here the needle and one of the quadrants are raised to the same potential (with respect to the other quadrant $Q'$). The applied voltage may be either alternating or direct in this case since the needle is attracted (rotated) in the same direction whether it is positive and the free quadrant $Q'$ negative or vice versa. It is to be noted that the instrument does not use any current when operated in the heterostatic or idiostatic manner.

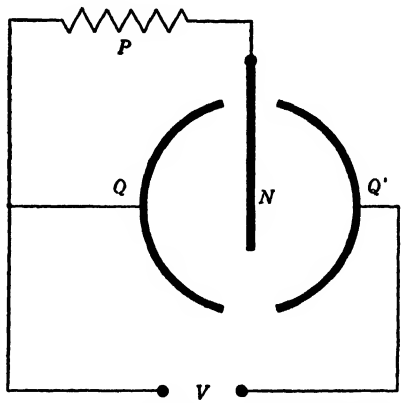



FIG. A–4. "Idiostatic" voltage connection of an electrometer.

Figure A–5 shows the connection for measuring a small current passing between the plates $A$ and $B$. Charges of electricity formed in the gas between $A$

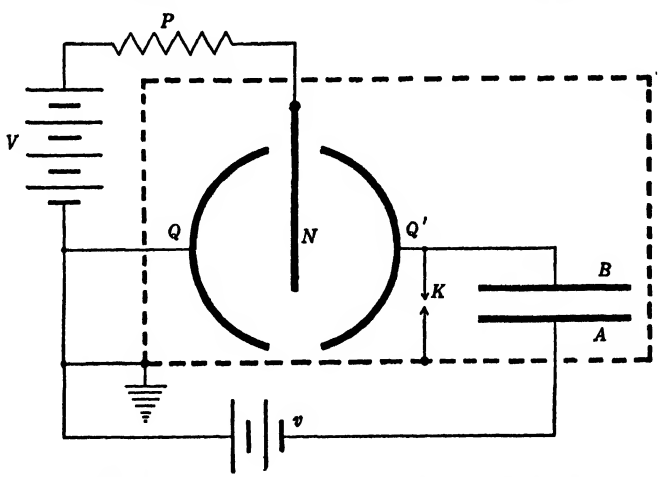



FIG. A–5. Measurement of small current with an electrometer.

and $B$ (by a radioactive substance, X-rays, ultra-violet light, etc.) are driven to plate $B$ by the accelerating potential $v$. As the charge builds up on $B$ and $Q'$, the needle is deflected

at a rate depending on the strength of the current from $A$ to $B$. $K$ is a grounding key short circuiting the quadrants and is only opened at the time readings are being taken. This key should be closed when the battery $v$ is first connected, to prevent the large induced charge on $B$ from reaching the quadrant. It is important that the quadrant $Q'$, the key $K$ and the plate $B$ be carefully shielded at all times with a grounded metal case in order to prevent the addition of induced charges to those collected from between the plates $A$ and $B$. This is indicated in figure A–5 by the dotted lines.

**Calibration for Voltage Measurements.**

There are three things to be considered in calibrating an electrometer for voltage measurements; first, the voltage sensitiveness or number of millimeters deflection on a scale one meter away caused by one volt across the quadrants; second, the variations of the sensitiveness with deflection and with needle potential; third, the period of free swing. It is desirable that the sensitiveness be constant over the entire scale and that it be high when dealing with small differences of voltage, even at a sacrifice of the range of the instrument. Further, the period must not be too great for convenience in making the readings.

The curve showing the deflections at increasing voltage across the quadrants (constant needle potential) is not, in general, a straight line. In other words, the voltage to cause a deflection from 0 to 3 centimeters is not the same as that from 3 to 6 centimeters, etc. The elementary theory (Starling, "Electricity and Magnetism," p. 157, 4th Edition) of a Dolezalek electrometer leads to the following equation for the deflection $\theta$ (radians rotation of the needle),

$$\theta = K(v_1 - v_2)\left(V - \frac{v_1 + v_2}{2}\right) \qquad \text{(A–1)}$$

where $K$ is a constant, $v_1$ and $v_2$ are the potentials of the quadrants with respect to the ground and $V$ is the potential of the needle with respect to the ground.

With the idiostatic connection, the needle is connected directly to one of the quadrants, and $V = v_1$ so that equation A–1 reduces to

$$\theta = \frac{K}{2}(v_1 - v_2)^2 = \frac{K}{2}v^2 \qquad \text{(A–2)}$$

stating that the deflection is proportional to the square of the potential difference between the quadrants. Thus the Kelvin multicellular electrostatic voltmeters are provided with a "squared" scale.

With the heterostatic connection, the needle potential $V$ is great compared to the potentials of the quadrants, i.e., $V > \frac{v_1 + v_2}{2}$ so that equation A–1 reduces to

$$\theta = KV(v_1 - v_2) = KVv$$

where $v = v_1 - v_2$

and the sensitiveness is $S = \frac{\theta}{v} = KV$ (A–3)

stating that the deflections are linearly proportional to the quadrant voltage. This is found to be nearly true in practice but for accurate work it is necessary to calibrate the scale in terms of volts or to use a small part of the scale near the zero reading.

Equation A–3 also indicates that the deflections are directly proportional to the potential of the needle. This is far from true in practice. In the elementary theory, the electrostatic field between the needle and quadrants is assumed to be uniform. Obviously there is a distortion of the lines of force at the edges of the conductors which is different with different positions of the needle. This electrostatic distortion* introduces a couple, sometimes aiding and sometimes opposing the restoring couple of the twisted suspension. The direction of this couple depends on the construction and adjustment of the instrument. Results obtained experimentally are shown in figure A–6. Curve *ab* is for the

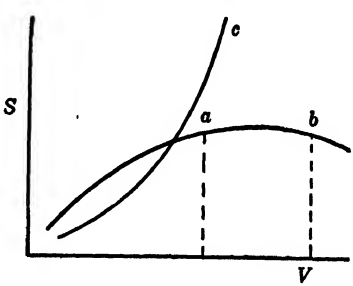



FIG. A–6. Sensitiveness of an electrometer with various needle potentials.

* The theory is discussed in Chapter I of Makower and Geiger's "Practical Measurements in Radioactivity." This leads to the corrected form for sensitivity given by

$$S = \frac{\theta}{v} = \frac{K_1 V}{K_2 + K_3 V^2}$$

for the case where the electrostatic distortion couple aids the mechanical restoring couple. The K's are constants.

case where the electrostatic distortion couple aids the mechanical restoring couple and shows that between points *a* and *b* the needle potential may vary considerably without appreciably affecting the sensitiveness. Curve *c* is for the case where the two couples oppose each other and shows that very high sensitivity may be obtained. When the electrometer is in this condition, a very small change of needle voltage causes large variations of the sensitiveness and may even throw the instrument into an unstable condition.

**Calibration for Current Measurements.**

The quadrant electrometer is generally used to compare different currents but may be used in an absolute determination. In the former case, the rate of deflection of the needle, taken over a given part of the scale and with fixed needle potential, is measured for the different currents. If this is not too large, it is directly proportional to their relative strengths. This linearity can be seen from the following considerations. The current $i$ is that due to a flow of $q$ units of electricity (usually in e.s.u.) between the plates of the ionization chamber ($A$ and $B$ of figure A–5) in a time $t$. If the capacity of the upper plate and quadrant ($B, Q'$) is $C$ and its voltage increase is $V$, then

$$i = \frac{q}{t} = \frac{CV}{t} \tag{A-4}$$

Now, in the discussion of voltage calibration, it was shown that the deflection may be considered as roughly proportional to the voltage increase on the quadrant. Hence we have

$$i = \frac{C}{S'}\frac{\theta}{t} = K'\frac{\theta}{t} \tag{A-5}$$

where $\frac{1}{S'}$ is the constant of proportionality. Now $K'$ will not be a constant if the capacity $C$ varies with the needle position or if $S'$ changes in any way. Both of these quantities do change somewhat and $S'$ is a complicated function of the needle potential.*

$$* \; S' = \frac{\theta}{v} = \frac{K_1 V}{K_2 + K_3 V^2 + \frac{K_4}{C} V^2}$$

This is due to four couples; first, the electrical couple of attraction and repulsion of the electrical charges; second, the mechanical restoring couple; third, the electrostatic distortion couple, and fourth, an additional damping effect caused by the reaction of the charges set up on the quadrants by the motion of the charged needle, known as the inductional electrostatic control. This last is analogous to the damping effect of a loop of wire on the moving coil of a galvanometer. Thus, in order that the rates of deflection of the needle of the quadrant electrometer may be taken as proportional to the currents to be compared, it is necessary to use the same part of the scale and to keep the needle potential fixed.

To measure a current in electrostatic units, observe the time $t_1$ for a deflection of $\theta$ centimeters (about 10) on the scale. This was caused by a charge of amount $q_1$ e.s.u., collecting on the quadrant. If $C$ is the capacity (e.s.u.) of the insulated quadrant and all connected apparatus with respect to the ground, then

$$q_1 = it_1 = Cv = K\theta \qquad \text{(A–6)}$$

where $v$ is the increase in voltage due to charge $q_1$. This may be obtained from the voltage-deflection calibration previously discussed. Now connect a small standard condenser of capacity $C_0$ (10–50 e.s.u.) in parallel with ionization chamber. It will now require a longer time $t_2$ for the same current $i$ to give the same deflection $\theta$. Then

$$q_2 = it_2 = (C + C_0)v = K\theta \qquad \text{(A–7)}$$

Whence

$$i = \frac{C_0 v}{t_2 - t_1} \text{ e.s.u.} \qquad \text{(A–8)}$$

The standard condenser may consist of two long concentric metal cylinders of nearly the same radius. Its capacity can then be computed from

$$C_0 = \frac{l}{2 \log_e \frac{a}{b}} \text{ e.s.u.} \qquad \text{(A–9)}$$

where $l$ is the length of the shortest cylinder (in centimeters), $a$ is the inside diameter of the outer cylinder and $b$ is the outside diameter of the inner cylinder (in centimeters).

**Calibration for Quantity Measurements.**

If a quantity of electricity $q$ is placed on an insulated quadrant system having capacity $C$, the needle will be deflected to a voltage $v$. Then

$$q = Cv \tag{A–10}$$

where all values are measured in the same units. Then $v$ is obtained from the voltage-deflection curve.

In order to determine the capacity $C$, a procedure identical to that just given for measuring the absolute value of a current may be used. Equations A–6 and A–7 give

$$C = C_0 \frac{t_1}{t_2 - t_1} \tag{A–11}$$

The inductional method of Harms (see references) offers greater accuracy in determining the capacity of an electrometer than that just described. Although simple in operation, its discussion is too detailed to be included here.

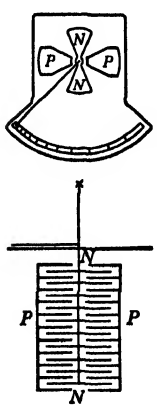



FIG. A–7. The Kelvin electrostatic voltmeter.

**Various Forms of Electrometers.**

The previous discussion has centered about the Dolezalek type since it is the most widely used of the various forms. Many other types have been designed, some using only two quadrants, others as many as six sectors in place of the usual four of the quadrant form. In some, the potential, current or quantity to be measured is applied to the quadrants while, in others, the needle is used and the quadrants are raised to a fixed potential. In the following paragraphs, a note is given on each of the principle types.

The needle $N$ of the Kelvin electrostatic voltmeter of figure A–7 is constructed of several thin, figure-eight-shaped aluminum plates suspended horizontally at their centers at equal distances along a vertical suspension. These move toward and between the two sets of fixed plates $PP$ (one for each end of the needle). One set of fixed plates and the needle are connected to one terminal of the instrument while the other set of fixed plates is joined to the second binding post, so that the meter operates idiostatically. The

instrument is rugged in construction and covers a wide range of voltages (zero to many thousand) either A.C. or D.C. Unlike the D'Arsonval type meters, it does not use any current for its operation. It requires levelling before being used.

In the Compton electrometer of figure A–8 the construction is the same as for the Dolezalek type except that the needle $N$ is tilted slightly along its axis and one quadrant $Q$ is moved a little above or below the plane of the other three. In this way unusual sensitiveness (15,000 millimeters per volt) may be obtained without unduly sacrificing the uniformity of the scale deflections or the rapidity with which readings may be taken. The instrument is more difficult to handle in its highly sensitive state than the Dolezalek type.

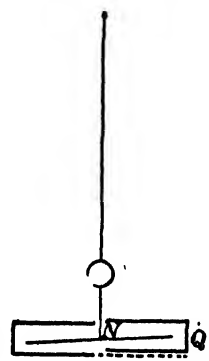



FIG. A–8. The Compton electrometer.

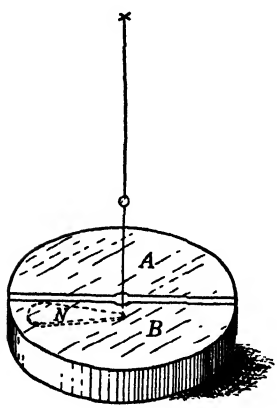



FIG. A–9. The Hoffmann electrometer.

The Hoffmann electrometer of figure A–9 uses a needle suspended in a small pill-box-shaped metal chamber which has been cut into two parts. For this reason, it is sometimes referred to as a binary or duant electrometer, as contrasted with the quadrant form cut into four parts. These binants (halves) $AB$ are raised to a small fixed potential (1–12 volts) and the charge to be measured is applied to the needle $N$. This needle is an extremely thin platinum sheet suspended at one end (instead of the middle) and located symmetrically with respect to the two halves, close to the lower plates. The binants are surrounded with a heavy metal sheath to help maintain a constant temperature. The instrument has a voltage sensitiveness about equal to that of the Dolezalek type but, in view of its small capacity (about 5 e.s.u.), it is able to record much smaller quantities and currents of electricity. For example, it has been used to measure the ionization produced by a single alpha particle.

In the Lindemann electrometer of figure A–10, the suspension *S* is clamped at both ends and the needle *N* (which is really needle-shaped) has its center fixed at the center of the suspension (forming a cross) and each end lies between two metal plates. These four plates *PPPP* are connected in pairs and act in the same fashion as the quadrants of the Dolezalek electrometer. The motion of the needle is observed with an ordinary microscope. The end of the needle can be made to move about three-quarters of a millimeter per volt so that with an X20 eyepiece in the microscope a sensitivity of around 500 divisions per volt can be attained. The capacity is from 1 to 3 e.s.u. and the needle takes up its final position in from one-fifth to one second (the smaller value for a smaller sensitivity). Further, in view of the method of suspension, the instrument may be tipped in any desired position.

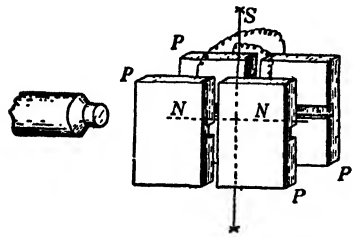


FIG. A–10. The Lindemann electrometer.

The Wulf string or bi-filar electrometer of figure E–6 is constructed with two long (6 centimeter) platinized quartz fibers *LL* joined together at both ends and suspended by an amber plug. The fibers are stretched from the lower end by a small weight or from the center of a bow-shaped quartz fiber *B* in case the instrument is to be moved about. On applying a charge, the fibers separate from each other by an amount which, observed at their center by a microscope, is directly proportional over a wide range to the voltage applied. The capacity (2 or 3 e.s.u. in operation) and the period of such a system are very small and the sensitiveness is much greater than that of a gold leaf electroscope.

The single fiber electrometers of figure E–7 use a fiber hanging or stretched between two metal knife edges which are usually charged to a relatively high fixed potential. Motion of the fiber is observed with an ordinary microscope. The capacity is small (1 to 10 e.s.u.). The sensitiveness can be made as high as 300–1000 divisions per volt and a wide range of voltages (0.001 to 100) may be measured. This instrument, like the Wulf and Lindemann electrometers, has the great advantage of quick response and absence of oscillations.

## EXPERIMENT A-1

### A STUDY OF A QUADRANT ELECTROMETER

The purpose of this experiment is to study the adjustment and to measure the voltage sensitiveness of a quadrant electrometer under various conditions.

*Adjustment.* — 1. Carefully raise and suspend the needle as nearly as possible in the center of the quadrants. Two of the quadrants should lie entirely on one side and two on the other side of a line joining the center to the middle point of the scale.

2. The adjustment of the electrometer requires leveling so that the needle will remain in its symmetrical position when the needle potential is applied. Connect as in figure A–3 with a needle potential ($V$) of about 100 volts (it may be positive or negative), with the quadrant voltage ($v$) = 0 and with the quadrants both grounded.

3. Charge and discharge the needle. If the needle swings to one side, the leveling may be altered so as to make it return to the zero position. It will usually be found that one leveling screw is more effective than the others in making the adjustment. If the zero position keeps changing (drifts), tighten the suspension screws, resolder the suspension joints or put in a new one.

4. Apply a small voltage to the quadrants ($v$ = 1 volt). If the deflection creeps back to zero, clean the insulators with ether.

*Voltage Calibration.* — 1. A convenient arrangement for applying various potentials is indicated in figure A–11. Four or five dry

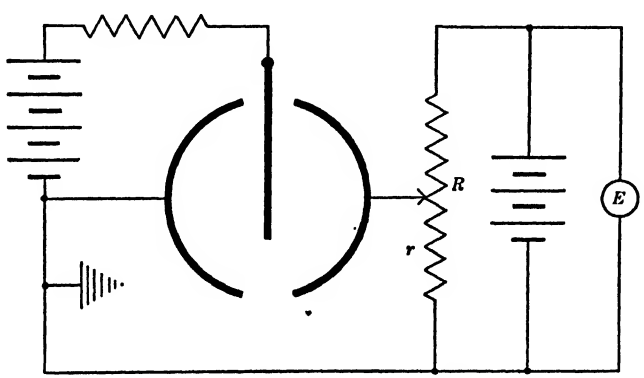



FIG. A–11. Voltage calibration of an electrometer.

cells are connected across a high resistance box (10,000 ohms or more). The total voltage $E$ is read on a voltmeter. A plug is used to tap off a known voltage, $v = \frac{r}{R}E$.

2. Observe the deflection obtained for various potentials applied to one quadrant, with a fixed needle potential (say 15 volts). Deflections up to 20 or 25 centimeters on each side of the zero position should be used.

3. Repeat (2) using, in each case, needle potentials of 30, 60, 120 volts.

4. Plot the various values of quadrant potentials, positive and negative, as abscissæ and the deflections from zero as ordinates for the different needle potentials. Draw all curves on the same chart. Note the range over which the deflections are directly proportional to the quadrant potentials.

5. Plot deflections as the ordinates and needle potentials as the abscissæ, maintaining a definite potential on the quadrants (say 2 volts). Note the deviation from a straight line and state on the curve whether the distortion couple is aiding or opposing the mechanical couple.

6. Compute the voltage sensitiveness of the instrument under the most favorable condition, recording its value on the chart of part 5.

*Precautions.* — See that the various parts of the electrometer are connected so as to have definite relative potentials.

Do not fail to include the protective resistance $P$ in all of the connections as ind cated.

## EXPERIMENT A–2

### CURRENT AND QUANTITY MEASUREMENTS

See the experiment at the end of chapter 1.

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# APPENDIX B

## THE PRODUCTION OF VACUA

**Introduction.**

Some pumps operate from atmospheric pressure, while others require that a "fore pump" reduce the pressure considerably before they will start pumping. The speed of a pump may be measured by the number of liters of gas removed each minute, the volume being reduced to its equivalent at atmospheric pressure. For example, a good oil pump will remove 5 or 6 liters per minute. With pumps requiring a fore vacuum, the speed depends on the vacuum produced by the fore pump. The speed of evacuation of an enclosed system depends not only on the speed of the pump but also on the size of the connecting tubes and the gases and vapors present or given off by the walls.

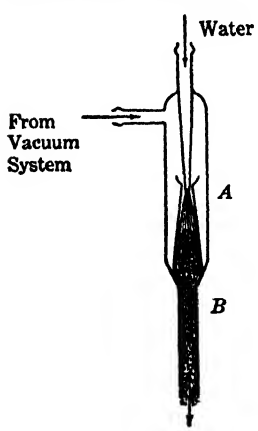


FIG. B–1. The water aspirator.

**Pumps Working From Atmospheric Pressure.**

The *water aspirator* or filter pump shown in figure B–1 may be used if only a moderate degree of evacuation is desired. Water, under a pressure of ten to twenty pounds per square inch, passes through the constricted tube at *A*, dragging along the air in the surrounding chamber. This air forms a sheath around the water for a short distance, then mixes with it to pass out at *B*. Such pumps are fast but cannot reduce the pressure much below that of the vapor pressure of water at the existing temperature. This amounts to 9 mm. at 10° C. and 20 mm. at 23° C.

The *Toepler* pump, *EFGH* of figure D–5, may be used to reduce the pressure to as low a value as $2 \times 10^{-5}$ mm. but works slowly as the operation is carried on by hand. It is more often used in the collection of gases as described in connection with the figure. However, its action as a pump in evacuating the bulb *D* is as follows. The gas in *F* is compressed by lifting the mercury reser-

voir $E$ and is forced out through the capillary tube $H$. $E$ is then lowered, gas expands from $D$ into $F$ and the process is repeated. The side tube $G$ serves to prevent excessive bumping of the mercury as it is being lowered, which is caused by the gas from $D$ expanding into $F$ when the pressure in the former exceeds that in the latter.

One of the many forms of *oil pumps* is shown in section in figure B–2. A rotor $A$, mounted eccentrically on its shaft, moves in the

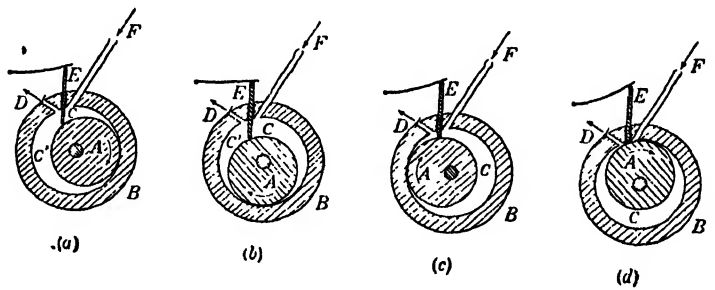


FIG. B–2. The "Cenco" oil pump.

direction of the curved arrows inside the cylinder $B$ at 200 to 300 revolutions per minute. In stage *a* of the figure, gas from the chamber to be evacuated enters the chamber $C$ which it continues to fill in stages *b* and *c*. As the cylinder $A$ continues its rotation, this gas occupies the chamber $C'$ which becomes smaller in the successive stages. In this way the gas is compressed and forced out through the valve $D$. The inlet and outlet chambers, $C$ and $C'$, are isolated from each other by the oiled vane $E$ which is held in close contact with the rotor by a spring at its top. Two such pumps are mounted on the same shaft with a small phase displacement to each other, connected in series and immersed in oil. A valve is provided at the inlet $F$ to prevent oil being sucked back into the evacuated system. Such pumps operate at approximately six liters per minute and, when new, can reduce the pressure to $10^{-3}$ mm.

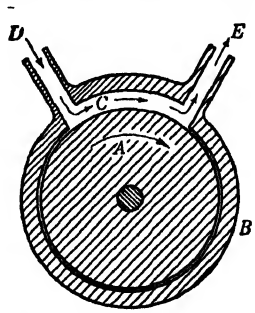


FIG. B–3. Principle of molecular pumps.

**Pumps Requiring a Fore Vacuum.**

The principle of *molecular pumps* may be seen in figure B–3. The cylinder *A* rotates clockwise in its casing *B* with such velocity that a point on its periphery travels faster than the molecules of the gas in the partially evacuated groove *C*. Such particles as strike this moving drum are given a tangential velocity in the direction of motion. Hence, particles which enter at *D* are given a motion toward the outlet *E* where they are removed by the fore pump.

In *Gaede's molecular* pump, half of which is shown schematically in figure B–4, the rotating drum *A*, of about 10 cm. diameter, con-

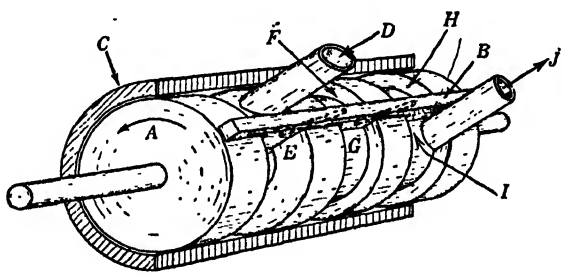


FIG. B–4. Gaede's molecular pump.

tains several narrow and deep circular grooves. A set of vanes *B* fit closely into these grooves, with a clearance on all sides of about 0.1 mm. The drum is surrounded by an airtight casing *C* whose clearance is only 0.01 mm. Air entering at *D* is piled up at *E* and passes to *F* through slots indicated by the hole in *B*. From *F*, it is moved to *GHI* and *J* where it is removed by a fore pump. The first groove, actually at the center of the whole drum, is deeper (23 mm.) than the others (13 mm.) as the pressure is lower here. The drum is rotated at high speeds, from 2500 to 12,000 revolutions per minute, since the greater the speed the greater the pressure difference it can set up. At a speed of 12,000 r.p.m. and with a fore pressure of 0.05 mm. it can evacuate to $2 \times 10^{-7}$ mm. Since the pump depends directly on molecular action, it can eliminate both gases and vapors. At $10^{-3}$ mm., this type can remove 80 liters (reduced to atmospheric pressure) per minute.

*The Holweck molecular* pump of figure B–5 is an improvement of that of Gaede. The gas from the chamber to be evacuated

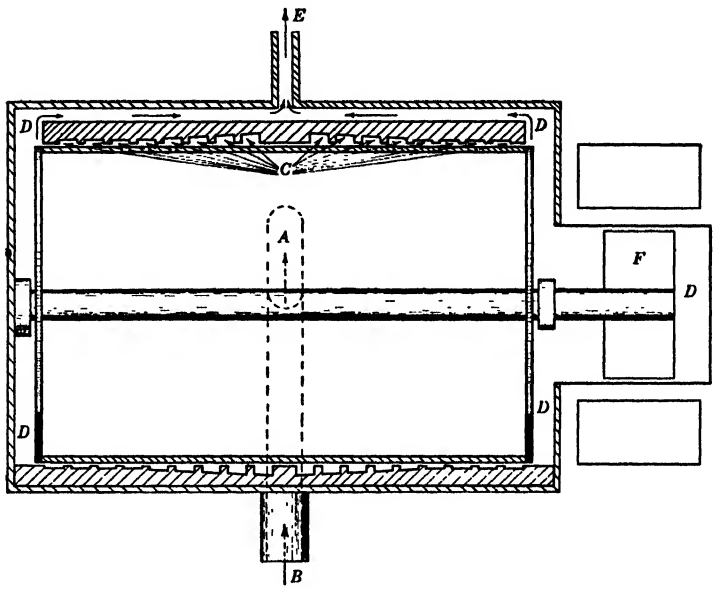


FIG. B–5. The Holweck molecular pump.

enters at *A* through the large tube *B* and is moved through the left- and right-handed spiral grooves *C* cut in the casing, reaching the partically evacuated regions *D* where it is drawn off by the fore pump at *E*. The armature *F* of the induction motor used to rotate the drum is enclosed in the fore vacuum so that leakage at the bearings is eliminated. The speed of these pumps is very great, 270 liters per minute having been recorded, so that the size of the tubing and conditions in the vacuum chamber play the major rôle in the speed of evacuation. Minimum pressures attainable are less than $10^{-6}$ mm.

By far the most outstanding pumps today are the *mercury condensation pumps*, as shown in figures B–6 and B–7. Their speed at the jet *C* is infinite, so that the rate of diffusion of the gases through the tubes of the system and the gases given off by the walls set the limit to the speed of evacuation. Theoretically, these pumps can create a perfect vacuum. Further, the only moving

part is a stream of mercury vapor. In figure B–6 the mercury vapor rising from the boiler *A* passes through the heat-insulated tube *B* to travel with considerable velocity through the constriction *C*. From here, it is condensed by the water jacket *D* and returns in liquid

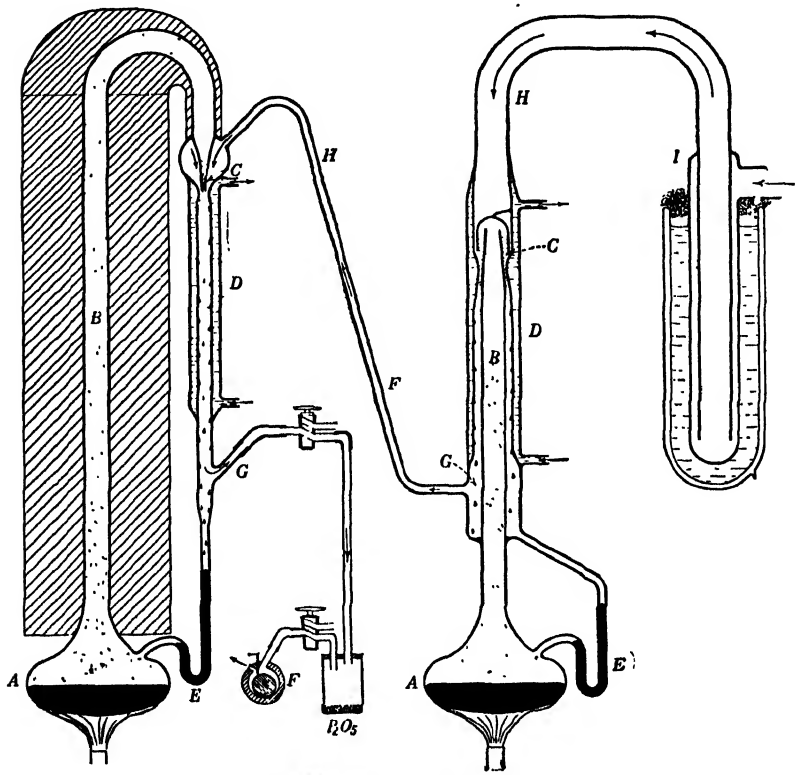


FIG. B–6. Mercury condensation pumps.

form through the U-tube *E* to the boiler, where it is reheated. The fore pump *F* maintains a pressure in the tube *G* considerably lower than that of the mercury vapor in the boiler. Gas from the chamber to be evacuated (*H*) diffuses to the region around the constriction *C* where it is entrained by the mercury vapor and carried away by the fore pump. Since the velocity of the mercury vapor particles at the mouth of the jet *C* is considerably greater than the diffusion rate of the gas molecules around it, the chance of diffusion of the gas molecules in the opposite direction is very slight (computed as 1 in $10^{20}$). Further, the mercury, being condensed im-

mediately below the jet, exerts no greater vapor pressure in $H$ than that which it has at room temperature. This is around $10^{-3}$ mm. and, for lower pressures, the liquid air trap $I$ is used to prevent mercury vapor from entering the remainder of the vacuum system.

In practice, it is found that the speed of these pumps depends on the size and shape of the jet. Pumps of the type shown at the right in figure B–6 do not usually "take hold" until the fore vacuum is lower than that created by water aspirators or oil pumps. Thus, a first stage pump of the type shown at the left is used as its fore pump. This insures the maximum speed of operation of each pump.

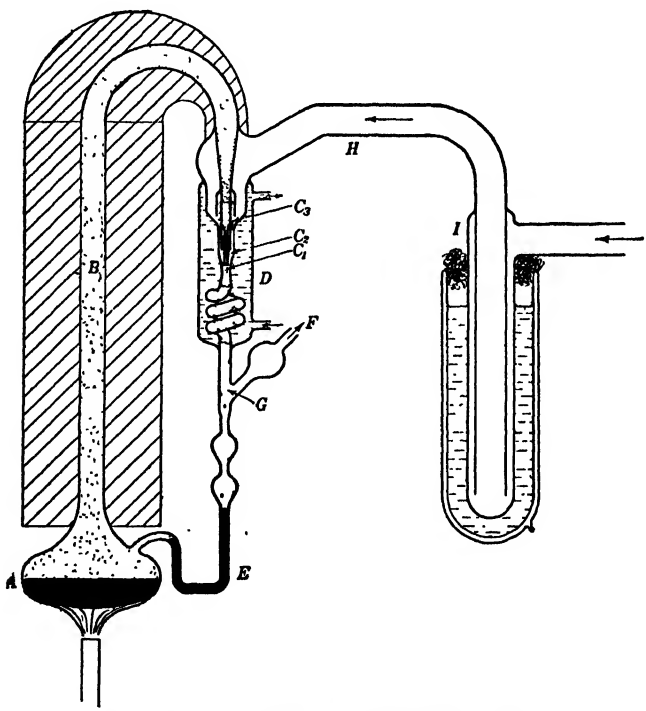


FIG. B–7. A three-stage condensation pump.

There are many forms of these mercury condensation pumps, some of which are constructed entirely of steel and contain two to four stages in series. These are used when the highest rate of pumping at low pressures is desired. In figure B–7 is shown a glass pump

containing *three stages* in one. The mercury is divided into three parts, that which passes through $C_1$ creating the fore vacuum for the second stage at $C_2$ which, in turn, lowers the pressure for the third stage $C_3$.

**The Elimination of Occluded Gases.**

At low pressures, the layer of water which sticks to glass surfaces begins to evaporate rapidly. After this has been removed, it is found that pumps, though capable of low pressures, cannot reach their limit. If the system is sealed off, the pressure slowly rises. This is due to the liberation of gases occluded in the glass and metal parts of the system. This takes place slowly at room temperatures and may be greatly hastened by heating the system. To "bake out" the glass it is raised for several hours to as high a temperature as it will stand without collapsing. Lead glass may be heated to 300° C., soft glass to 350° C., and pyrex to 450° C. Metal parts may be heated by passing an electrical current through them, by continued bombardment by electrons from a hot filament or by the use of an induction furnace which uses high frequency currents produced by the discharge of a condenser or by a vacuum tube oscillator.

**The Sorption Processes.**

Sorption is a property of certain substances for occluding and retaining gases and vapors. *Absorption* is a true solution in a solid and takes place rapidly at first, then more and more slowly. *Adsorption* consists of a condensation on the surface and is practically instantaneous. Certain *chemical reactions* may occur to reduce the amount of gas or vapor in a chamber. These three sorption processes may occur simultaneously.

*Charcoal* which has been previously freed from gases has the property of adsorbing large quantities of gases, especially at low temperatures such as produced by liquid air. Ordinary wood or cocoanut charcoal does not show this property to any appreciable extent until it has been subjected to a heat treatment at about 800° C., called "activation." Activated charcoal can be purchased on the market. Samples which adsorb appreciably at atmospheric pressure (as in gas masks) are not necessarily satisfactory for the

production of high vacua. For use in this latter connection, the charcoal is placed in a tube (figure B–8) in the vacuum system and heated to a dull red temperature for several hours, the pumps being kept in operation. The system is then sealed off from the pumps and the charcoal is cooled with liquid air. It then removes a large part of the remaining gases. With gases such as hydrogen and nitrogen, the pressure may be reduced to values between $10^{-6}$ and $10^{-7}$ mm. of mercury, each gram of charcoal adsorbing from 10 to 120 c.c. of the gas (reduced to 0° C. and 76 cm. pressure) but with neon or helium the adsorption is small, from 0.1 to 8.0 c.c. per gram. This offers a method of isolating these gases when mixed with others. Dewar found that considerable quantities of helium were taken up by charcoal cooled below liquid air temperatures, say 15° absolute. Oxygen, once adsorbed, is only given up by prolonged heating at high temperatures. In addition to the high adsorption capacity of the large surface offered by the porous nature of charcoal, it also serves to remove water vapor by capillary action.

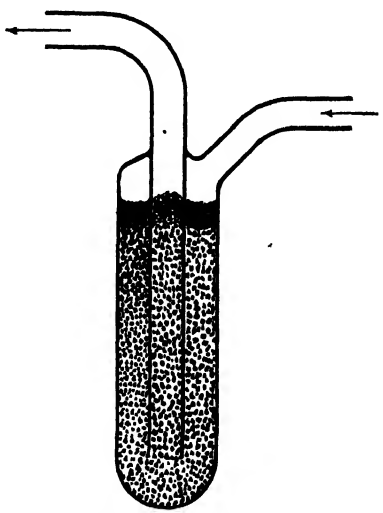

FIG. B–8. A charcoal tube.

Certain samples of *palladium black* have the property of absorbing hydrogen to a very marked extent. For producing high vacua, the palladium is heated to 100° C. in the system which is being evacuated. The pumps are then cut off and the palladium cooled with liquid air. Starting at $10^{-4}$ mm., the pressure will be lowered to around $5 \times 10^{-7}$ mm. Under certain conditions nickel, copper and iridium will also absorb appreciable quantities of hydrogen.

There are several methods for reducing the pressure after the vacuum chamber has been sealed off from the pumps. In one of these, zirconium, thorium or calcium is placed in the system before evacuation. After evacuating and sealing off, the substance is

volatilized by the external application of heat, when all except the rare gases such as argon, neon and krypton disappear. The initial pressure must not exceed a few millimeters if a high vacuum, say $10^{-7}$ mm., is to be obtained.

When an *electrical discharge* passes through a sealed Geissler tube, the common gases slowly disappear until the pressure is so low that the discharge ceases. This effect is observed in gas-filled X-ray tubes, so that it is occasionally necessary to admit traces of gas to prevent the tube from "hardening." The explanation of this "clean-up" is not known although the walls of the tube and the electrodes undoubtedly play an important part. This type of clean-up usually accompanies the process of sputtering.

The clean-up in an electrical discharge may be hastened by the use of phosphorus or magnesium. The tube is evacuated and sealed off. Then a small amount of the chemical is volatilized, a discharge being maintained between two electrodes. The discharge quickly disappears, showing that the residual gases have been cleaned up, while the chemical or "getter" condenses on the walls of the tube. With phosphorus as a getter, the tubes will then appear brown or reddish while with magnesium the coating will be silvery, like a mirror. The final pressures are of the order of $10^{-6}$ millimeters.

Nitrogen, oxygen and hydrogen slowly disappear from a low pressure tube in which a tungsten filament is maintained at high temperature. Pressures of the order of $10^{-6}$ mm. can be obtained by the use of such *incandescent filaments* when the preliminary pressure was only about 0.1 mm. Despite the great care in manufacture, X-ray tubes and kenotron rectifying tubes have a slight tendency to soften. But, if used from time to time, the slight traces of gas are removed and the tube remains hard.

## REFERENCES

S. Dushman, *The Production and Measurement of High Vacuum.* Also, under the same title, in the *General Electric Review*, 23, 1920; 24, 1921.

L. Dunoyer, Translated by J. H. Smith, *Vacuum Practice.*

F. H. Newman, *The Production and Measurement of Low Pressures.*

# APPENDIX C

## PRESSURE GAUGES

**Introduction.**

The pressure in vacuum systems may be measured in terms of the equivalent number of millimeters of mercury, or in bayres.* The bayre is the pressure exerted by a force of one dyne uniformly distributed over one square centimeter. One millimeter of mercury is equal to 1333 bayres and one bayre is equal to 0.752 $\mu$ of mercury, the $\mu$ being one one-thousandth of a millimeter.

Before using any of the gauges for *very* low pressures, it is necessary to remove all occluded gases by the baking out processes described in the chapter on the production of vacua.

For pressures where a Geissler discharge passes through the tube, the length of Crookes' dark space may be used as a rough measure of the degree of evacuation.

Several types of manometers for use at low pressures are shown in figures C–1 and C–2. In these figures (1) and (2) are the usual closed and open U-tubes of mercury.

**The McLeod Gauge.**

Figure C–1 (3) shows a McLeod Gauge in which the low pressure gas is compressed to a pressure easily observed. The large bulb with capillary tube on top has a volume $V$, determined at the time of construction. The gas, whose low pressure $p$ is to be measured, enters this bulb freely through the tube $A$. It is compressed by raising the mercury reservoir $B$ up to a point $C$, where it occupies a small volume $v$ at a pressure $P$. Then from Boyle's law,

$$pV = Pv \qquad \text{(C–1)}$$

The volume $v$ is equal to $\pi r^2 h$, where $r$ is the radius in mm. of the uniformly circular capillary bore (determined when the gauge was being manufactured) and $h$ is the distance in mm. to the top of the capillary. In the other side tube, the mercury rises to $D$, so that

* L. Dunoyer calls this unit the microbar. The "bar" = $10^6$ bayres.

$P = h'$, in mm. of mercury. This side tube is made of the same capillary tubing as $C$ in order that there be equal capillary depres-

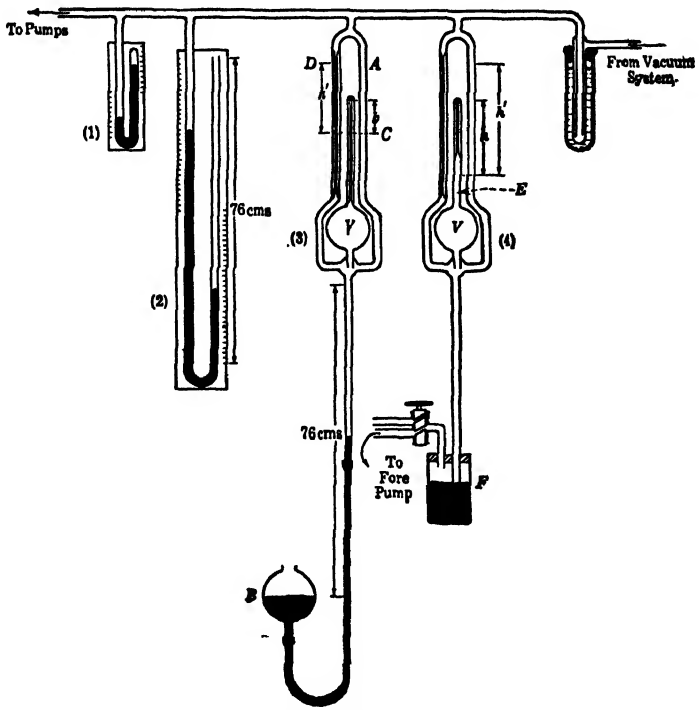


FIG. C-1. Pressure gauges.

sion on both sides. We then have,

$$p = \frac{\pi r^2 h h'}{V} \text{ mm. of mercury,} \qquad \text{(C-2)}$$

$V$ being measured in cubic millimeters. The gauge may be operated conveniently by making $h' = h$. Then we have

$$p = Kh^2 \qquad \text{(C-3)}$$

where $K$ is a constant ($= \pi r^2/V$). Then a scale calibrated for pressure may be placed along the central capillary tube. The instrument may be built to cover ranges extending from 1 mm. to $10^{-5}$ mm. With a bulb of 200 c.c. capacity and a capillary whose radius is 0.5 mm. and length is 20 cm., $K = 3.93 \times 10^{-6}$ and the

gauge reads conveniently from $10^{-5}$ to 0.16 mm. Two ranges of pressure may be measured by the same instrument if constructed with the larger tube $E$ of (4). This figure also shows a different method of raising the mercury. Air is removed from $F$ as the main system is being evacuated, and is admitted through the stop cock or pumped out to raise or lower the mercury. This gives a more convenient form of gauge and prevents air leaks through the rubber tube of (3). McLeod gauges do not measure vapor pressures. It

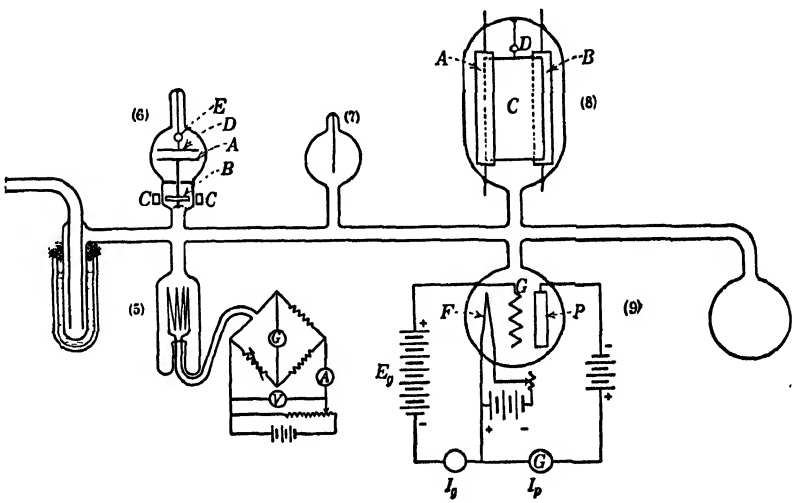


FIG. C–2. Pressure gauges.

is important that the glass, rubber and mercury parts be scrupulously cleaned before assembling.

**The Pirani Gauge.**

The Pirani gauge (5) of figure C–2 operates on the principle of thermal conductivity; the higher the pressure, the greater the rate at which heat is conducted away from a hot filament sealed in the vacuum system, and vice versa. Maintaining constant current through the filament, its temperature and also its resistance change with the pressure of the gas and may be measured with a Wheatstone Bridge. The greater the pressure, the lower the resistance. The gauge is calibrated by comparison with a McLeod

gauge, a liquid air trap being placed between the two to freeze out the mercury vapor. It has been found better to maintain the filament at constant temperature, observing the voltages $V$ necessary to do this as the pressure changes. The greater the pressure, the greater the reading of the voltmeter. If $V_0$ corresponds to the lowest pressure attainable and $V$ to a higher pressure, it is found that $(V^2 - V_0^2)/V_0^2$ plotted against the pressure gives a straight line below 0.05 mm. which is the same for all gases containing no hydrogen. However, separate curves for each gas containing hydrogen must be made. Pressures as low as $10^{-5}$ mm. can be measured. Readings may be obtained quickly, especially by the first method described, if the gauge is placed in a constant temperature bath. Recording meters may be used to obtain permanent records. In practice, a tungsten filament lamp (10–40 watts) with rigid filament may be used for this gauge. Using the constant temperature method, the bridge is balanced at the start so that the filament is around 100° C., i.e., below red heat.

**Molecular Gauges.**

The molecular gauges (6) and (7) operate on the principle of viscosity. In (6) the disc $A$ is rotated by the magnet $B$ turned by the rotating magnetic field $C$. As a result, the light disc $D$, supported by a quartz fiber, is deflected by the viscous drag of the intervening gas. The distance between the discs must be small in comparison to the mean free path of the molecules at the existing pressure. The speed of $A$ remaining constant, the angle of twist of the suspension, as observed by the reflection of light from the mirror $E$, is proportional to the pressure. This gauge, like that of (7), is calibrated by means of a McLeod gauge and is delicate, requiring skill to operate.

The vibrating fiber gauge (7) consists of a quartz thread suspended in the system. The rate at which its vibrations are damped down gives a measure of the pressure of the gas. The instrument has a range from 1.0 mm. down to $10^{-4}$ mm. but is not satisfactory for lower pressures.

**Radiation Gauges.**

A type of Knudsen radiation gauge is represented by (8). This operates on the principle of the repulsion between a hot and

cold plate due to molecular bombardment. The electrically heated platinum strips *A* and *B* act as the hot plate and the mica sheet *C* as the cold plate. The latter, supported by a quartz fiber, is rotated by the unequal bombardment on the sides adjacent and away from the hot plate, as observed by light reflected from the mirror *D*. The amount of rotation is proportional to the pressure, other conditions remaining constant, and the distance between it and the hot plate being small in comparison to the mean free path of the molecules at the existing pressure. When the gauge has been properly designed, the pressure may be calculated directly from the rotation, spacing, temperature difference, etc., so that it serves as an absolute manometer from $10^{-3}$ mm. to $10^{-7}$ mm. and possibly lower. This is the most accurate absolute instrument for work at extremely low pressures but requires skill in construction and use.

**Ionization Gauges.**

The ionization gauge (9), due to Buckley, has been found particularly useful, especially at low pressures. Electrons from the hot filament *F* are accelerated toward the grid *G* by the battery $E_g$. Some of these reach the grid and constitute the current $I_g$ (0.5 to 20 milliamperes) while others pass through into the region between the grid and negatively charged plate *P* where they are repelled back to the grid. The gas in this region is ionized by these electrons in proportion to the number of particles present and hence in proportion to the pressure. The positive ions so formed are drawn over to the plate giving a reading on the galvanometer of amount $I_p$. The current $I_g$ is kept at a constant value, say 20 milliamperes, by adjusting the filament rheostat. Calibration of the gauge by comparison with a standard gauge at pressures around $10^{-3}$ mm. then gives *K* in the equation,

$$P = KI_p$$

This equation may then be used for pressures down to $10^{-7}$ mm. At higher pressures, the current $I_g$ must be smaller, say 5 milliamperes, in order that this linearity hold true. The gauge requires separate calibration for every kind of gas used. A recording instrument may be used for $I_p$. A three-electrode radio tube containing no "getter" may be sealed to the vacuum system and used for this gauge.

## REFERENCES

S. DUSHMAN, *The Production and Measurement of High Vacuum.* Also, under the same title, in the *General Electric Review*, 23, 1920; 24, 1921.

L. DUNOYER, TRANSLATED BY J. H. SMITH, *Vacuum Practice.*

F. H. NEWMAN, *The Production and Measurement of Low Pressures.*

# APPENDIX D

## VACUUM TECHNIQUE

**Introduction.**

The lower the pressure to be obtained, the greater the care needed in the assembly of the vacuum system. For comparatively high pressures, above say 0.1 mm., rubber tubing, greased stop cocks, waxed joints, etc., may be satisfactorily used. But for lower pressures, all connections should be made of glass while metal parts, waxed joints, stop cocks and other sources of vapor pressure should be eliminated wherever possible. For very low pressures, all parts must be baked out for long periods of time to drive out the occluded gases. With mercury condensation pumps or mercury gauges, it is necessary to freeze out the mercury vapor with liquid air or carbon dioxide snow if the pressure is to be lowered below $10^{-3}$ mm.

**Leaks.**

Despite great care in the assembly of a vacuum system, it is usually found that there remain small holes or cracks too small to be visible. When these are comparatively large, blow into the system through a drying tube or apply a few pounds of compressed air and go over the outside with soap suds. Bubbles appear at the leak.

When the pressure can be reduced so that a discharge passes through, the leaks may be located with a spark coil. This should have a spark gap in parallel with its secondary to prevent high potentials which would spark through weak spots in the glass. Connect one terminal of the secondary of the coil to an electrode sealed in the system. If there is no electrode, stick a pin through the rubber tubing of the fore vacuum line and wax around it. A wire from the other terminal is held by a long glass rod and carefully moved over all parts of the system. The pressure being low enough, a bright spark occurs through the pin hole and the system lights up when the exploring wire is near the leak.

Another method for hunting leaks is to pass a discharge through the system and sponge over it with ether or water. With air in the tube, the color changes from a pinkish to a bluish when the water passes through the hole.

When the leak has been found, let in the air and fuse the hole. As a last resort, the leak may be eliminated by covering it with shellac or wax, but this introduces vapors into the system and cannot be used for very low pressure work, especially on parts which are to be heated. Red sealing wax may be used or a good wax may be made of about 90 parts rosin and 10 parts beeswax. The beeswax is melted in boiling water to free it from sugar granules. When cooled, it forms a cake on top of the water and is taken off and dried, then melted with the rosin. A pan of this mixture is kept on hand and melted whenever needed. The liquid is applied to warmed parts of the system with a brush. Softer waxes are formed by using a larger percentage of beeswax. DeKotinsky, Everett and Picein waxes of low vapor pressure may be purchased on the market.

Stop cocks should be tested for leaks before sealing into the system by holding in a vertical position, pouring a drop or two of ether or alcohol into the tube (the cock being greased and closed), quickly sucking on the same tube, putting the tongue on the end and watching if any bubbles come through the liquid. Turn a stop cock leisurely when using it and as seldom as possible for the grease is ultimately squeezed out leaving rings which leak. Never twist the stopper unless the grease is present or the glass walls will be scratched and leak.

Cast iron leaks badly and should be avoided. Brass, aluminum, copper, steel, nickel, etc., may be used but must be baked out when dealing with very low pressures.

When a system is first evacuated, it is more difficult to lower the pressure than after it has been pumped out a number of times. This is due to a surface layer of water on the inside of the tubes. The presence of water vapor is often mistaken for a leak in the system itself. Phosphorus pentoxide ($P_2O_5$) in a side arm or in a bottle as in figure B–6 is very effective in absorbing water vapor. The oil in a fore pump should be freed from moisture by removing and boiling whenever the pump fails to operate at its normal rate.

. Pyrex has a great tendency to contain minute pin holes where it has been fused even though carefully worked in an oxygen flame.

Rubber tubing connections to glass should be made as follows. The glass is warmed gently so that a ring of wax can be melted around it a short distance from the end. The rubber tubing is slipped over this and gently flamed at its end. Rubber tubing, even of the thick walled "pressure" type, permits the passage of air through its walls at low pressures and should be used only in the fore-pressure lines.

**Cleaning Processes.**

Rubber tubing should be washed with a solution of caustic potash (sodium hydroxide, NaOH), then carefully washed in distilled water and dried.

For cleaning glassware, a saturated solution of potassium bichromate in sulphuric acid is used. This is much more effective if used hot. When cleaned, the glass should be carefully washed in distilled water and dried by drawing warm dry air through it.

A very simple and effective way of cleaning mercury is shown in figure D–1. Dry air from a calcium chloride (CaCl) tube is

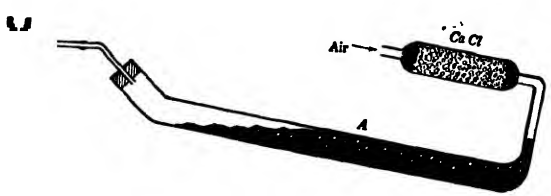


FIG. D–1. Cleaning mercury.

bubbled through the mercury *A* in a long tube (around 2 meters) for several hours. A heavy scum will form on the surface which contains practically all the impurities. The mercury is then filtered through small holes punched in filter paper held in a funnel.

A good but more tedious method of cleaning mercury is to filter it, and shake thoroughly in a bottle with chromic acid, then in water. Then let it fall in a fine spray from a cloth bag through several meters of dilute nitric acid, then through several meters of

distilled water and dry it by evaporation at around 350° C. A "drip" tube is shown in figure D–2.

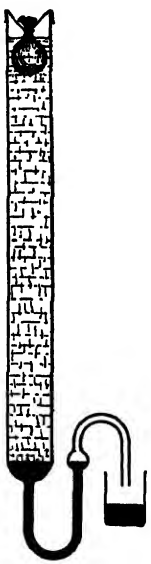

FIG. D–2. Cleaning mercury.

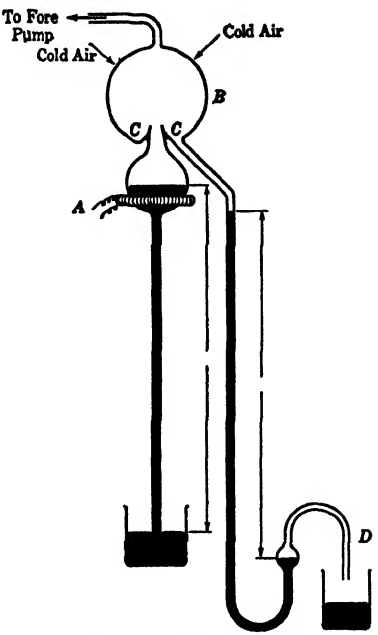


FIG. D–3. Distilling mercury.

Filtered mercury may be distilled in a vacuum with the apparatus shown in figure D–3 to obtain the cleanest mercury. The mercury is gently vaporized by the heater at *A* and condensed on the walls of the bulb *B*. It then falls into the groove *C* and runs out at *D*. About twenty pounds of mercury can be distilled in eight hours of continuous operation.

**Flow of Gases at Low Pressure.**

In experiments at low pressures, the rate of flow of the gas through various sizes of tubing is often of great importance. In many experiments pure gas is admitted continuously through a fine capillary or otherwise and pumped away by a mercury vapor pump. An equilibrium pressure is thus established in the experimental tube. If various parts are connected together, the pressure

may be very different in the different parts. In calculating the rate of flow with a good vapor pump, the pressure at the pump itself may be considered as maintained at zero. The flow through the various tubes may be computed from the following formula which may be derived kinetically. When the pressure is so low that the free path is large compared with the radius of the tube,

$$n = 2.22 \times 10^{19} \frac{R^3}{L} \frac{P_2 - P_1}{\sqrt{MT}} \qquad \text{(D–1)}$$

Here $n$ is the number of molecules of a gas of molecular weight $M$ passing per second through a tube of length $L$ cm. and radius $R$ cm. under a pressure difference $P_2 - P_1$ bayres at a temperature of $T°$ absolute. If $\frac{P_2 - P_1}{n}$ is defined as the "resistance" of the tube, it is easy to show that the "resistance" of a network of tubes connected in series and parallel is obtained by the same laws as for the combination of electrical resistances in series and parallel. It may be seen from the formula that a short narrow constriction offers as great a resistance to the flow of a gas as a long tube of larger radius. Thus, one centimeter of 0.1 cm. tubing offers the same resistance as ten meters of 1.0 cm. tubing. Thus, stop cocks and mercury cut-offs should be made of as large bore as possible.

A similar formula holds for the number of molecules flowing through an aperture of area $A$ sq. cm. in a thin disc:

$$n = 0.264 \times 10^{19} A \frac{P_2 - P_1}{\sqrt{MT}} \qquad \text{(D–2)}$$

In using a pressure gauge, it is important to have it connected as closely as possible to the experimental chamber and to wait a sufficient length of time before taking a reading to allow the pressure in the gauge to reach its new value.

**Vapors.**

Impurities in the system exert a constant vapor pressure below which it is difficult to lower the pressure, even with fast pumps and large tubing. For instance, if there is moisture in the tube at 20° C., the lower limit of pressure would be around 17 mm. The obvious solution of this very important vapor tension problem

is to eliminate as much as possible the causes of vapors and then to lower the temperature in a portion of the system. As water is cooled from 20° C. to −20° C., its vapor tension drops to 0.9 mm. At the temperature of carbon dioxide snow (−78° C.), it is 0.001 mm. and at liquid air temperature (− 195° C. to −182°.7 C.), it is below $10^{-6}$ mm. It is, therefore, necessary to remove water vapor with a tube of phosphorous pentoxide unless liquid air is available.

Next to water vapor, mercury vapor presents the greatest problem. Cooling methods must be used since mercury is used in the condensation pumps and McLeod gauges. The following table gives the vapor pressure of mercury at various temperatures.

| C | *P* mm. | C | *P* mm. |
|---|---|---|---|
| 40° | $6.0 \times 10^{-3}$ | −40° | $6.7 \times 10^{-6}$ |
| 20 | $1.8 \times 10^{-3}$ | −78 | $4.1 \times 10^{-8}$ |
| 0 | $3.5 \times 10^{-4}$ | −190 | nil. |

Other gases such as those from stop cock grease and pump oil have a pressure of only $10^{-4}$ mm. at 0° C. and are negligible at the temperature of carbon dioxide snow. Thus, if the water vapor is removed, carbon dioxide snow will serve excellently as a refrigeration agent although liquid air is still better. The liquid air in its Dewar flask or thermos bottle is raised around the trap slowly (see figure B–6) so that it does not boil too rapidly. After it has become quiet, a cotton or waste plug is added around the top of the flask to reduce the evaporation. It is best to reduce the pressure to a few centimeters before applying the liquid air.

To form carbon dioxide snow ($CO_2$), a cloth bag of about a liter capacity is tied over the opening of the drum of gas. The drum is tipped up at an angle of 30° or more with the valve at the bottom so it is below the level of the liquid $CO_2$ inside. The valve is opened wide when the liquid, rushing out under high pressure, soon turns to snow and collects in the sack. Break up the snow (do not pinch it with the fingers), put it in the Dewar flask and add ether, acetone or alcohol to form a slush. This insures good contact with the trap. A pint of $CO_2$ snow and alcohol will keep for about a day and a half. In many large cities, carbon dioxide snow is supplied

commercially in thick wooden containers under the trade name of "dry-ice."

**Mercury Cut-Offs.**

Figure D–4 shows two forms of mercury traps. When the vacuum chamber *A* is to be sealed off from the pumps, apply air pressure at *B*, raising mercury above the cut-off level *C*.

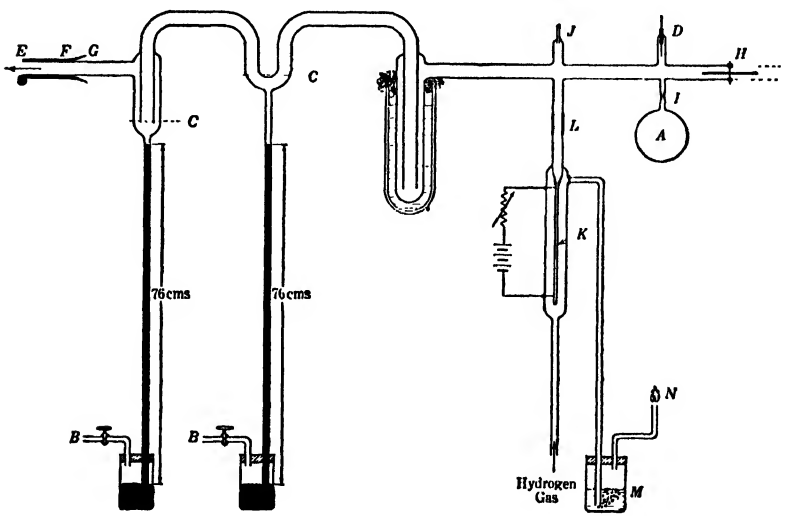


FIG. D–4. Vacuum technique.

**Metal-to-Glass Seals.**

Since the linear expansion coefficients of platinum and soft glass are the same, many lead-in wires are of this type. Dumet wire may be used similarly.

For lead-in wires with pyrex, tungsten may be used. (See *D* of figure D–4.) The tungsten is heated red hot and cleaned by rubbing with a stick of potassium nitrite. It is then washed, and warmed in a broad oxygen flame, when it quickly turns straw colored or purple. A thin tube of pyrex or G702P glass, which just fits over it, is slipped on and fused in a strong oxygen flame, starting at the middle and working towards both ends. When cool, the joint should have a smooth golden color if it is to be free from leaks.

In figure D–4, a copper tube *E* has been flared at its end and

thinned down by "spinning" in a lathe. This is first fused to the glass at *F*, after which the fusion is extended to *G* by blowing out the glass as the flame is advanced. The joint is then carefully annealed by cooling slowly. Either hard or soft glass may be used.

At *H* in the same figure, a copper foil is placed between the ends of two tubes. The glass is fused, then the right tube (dotted) is blown out and drawn away leaving a ring of glass on the face of the copper which is now fused to the other tube. Various electrodes may be put through this foil and soldered in place.

**Sealing Off.**

When a chamber is to be sealed-off from the system, a narrow constriction is made in the tubing as close as possible to the chamber, as at *I* in figure D–4. After pumping out, this constriction is warmed all over, the pumps being in operation to remove gases given off by the heated walls. Then a small flame is applied to the constriction, the tube fused together, and the chamber pulled off.

**Introducing Hydrogen.**

A palladium tube is sealed into the system as at *J* figure D–4. If a bunsen flame is applied with the tip of its inner cone (the oxidizing part) on the palladium, hydrogen will be drawn out of the system. If the outer part of the flame is applied, hydrogen will pass into the vacuum.

*K* is a platinum tube, some 20 cm. long, 1 mm. in diameter, with walls 0.1 mm. thick, sealed in a soft glass tube and attached to the pyrex system through the graded seal *L*. Tank hydrogen flows over the platinum tube at a rate indicated by the bubbling in the water *M* and is burned at *N*. If the platinum is heated to 500° C. by a battery (20 volts, 15 amperes) or a step down transformer, it allows pure hydrogen to flow slowly into the system. The hotter it is, the faster the hydrogen goes through. Thus, it may be used as a valve and also as a purifier of the gas entering the vacuum system.

**Purifying Gases.**

The main things to remove from tank hydrogen are oxygen and water vapor. Pass the gas through a calcium chloride tube, then over hot copper shavings or a hot copper wire (heated dull red),

then through a phosphorus pentoxide tube. The first and last tubes take out the water vapor and the copper combines with the oxygen to form copper oxide. Hydrogen mixed in proper proportion with oxygen or air is explosive so that the hydrogen should be passed through the system for a short time before heating up the copper. The safe condition may be determined by passing the gas, as it leaves the last tube, into an inverted test tube. When the gas has flowed for a short time, remove the test tube a few feet away, keeping it inverted, and apply a match. If the hydrogen burns rather than giving a gentle explosion it is safe to start the heating.

Tank nitrogen contains oxygen and water vapor which are removed as with hydrogen. It is not necessary to take any precaution against explosions.

Tank helium contains hydrogen and water vapor. The latter is removed with calcium chloride and phosphorus pentoxide as before. The middle tube should contain black copper oxide heated to dull red. The copper oxide combines with the hydrogen to form copper and water. Another way is to circulate the gas over heated, out-gassed charcoal, using liquid air to freeze out the vapors.

Any one of the rare gases may be purified by passing through a chamber in which a spark is occurring between misch metal electrodes, or an arc between calcium electrodes. Misch metal is a mixture of rare earths and absorbs nitrogen very readily.

Tank oxygen, made from liquid air, contains nitrogen which is difficult to remove. Water vapor should be taken out with phosphorus pentoxide. Oxygen from electrolysis contains water vapor and hydrogen which are removed with CaCl, $P_2O_5$ and heated copper oxide as in the case of helium.

Sticks of potassium hydroxide (KOH) in a side tube serve to remove carbon dioxide from the system.

**Collection of Gases.**

Figure D–5 shows the construction of a Toepler pump used in the collection of gases. The entire system is evacuated by applying a fore pump at *A*. Mercury is then forced above the cut-off point *B* by blowing at *C*. The gas is then generated at *D*. The mercury reservoir *E* is then raised so that the gas in *F* and *G* is cut off and compressed through the mercury in the capillary tube *H*

into the chamber *I*. *E* is then lowered, more gas expands into *F* and the process is repeated until the approximate pressure desired

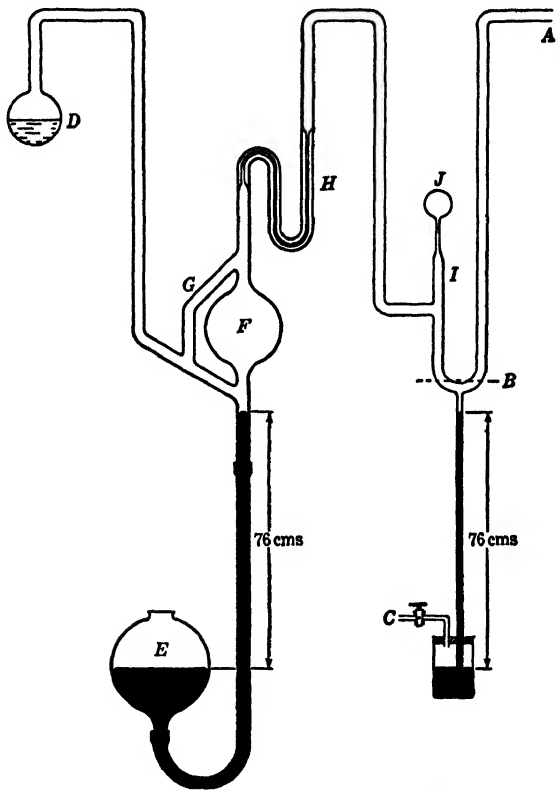


FIG. D–5. Collecting gases with a Toepler pump.

is obtained in *I*, as measured by the difference in height of the mercury in the U-tube. By changing the pressure at *C*, the gas in *J* can be brought to the exact pressure desired and sealed off at the constriction.

## REFERENCES

S. DUSHMAN, *The Production and Measurement of High Vacuum.* Also, under the same title, in the *General Electric Review*, 23, 1920; 24, 1921.
L. DUNOYER, TRANSLATED BY J. H. SMITH, *Vacuum Practice.*
F. H. NEWMAN, *The Production and Measurement of Low Pressures.*
L. B. LOEB, *Kinetic Theory of Gases*, pp. 256, 263.

# APPENDIX E

## ELECTROSCOPES *

Electroscopes have special designs according to the type of ray to be measured, the condition (solid, liquid or gas) and the strength of the active material. In the "solids" electroscopes of figures 8–1, E–1, 2, 3, the active substance is placed at XXX, ionizing the gas immediately above. When all three rays are sent out, they all contribute to the ionization current but, since the alpha rays are by far the strongest ionizers, the instrument is spoken of as an *alpha ray electroscope.* In figure E–2 the leaf system (*L*) is

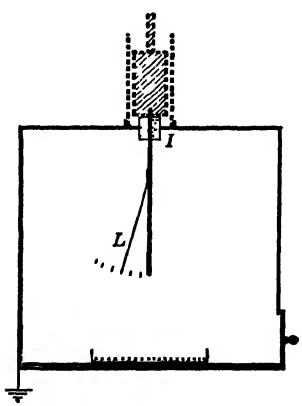


FIG. E–1. An alpha ray electroscope.

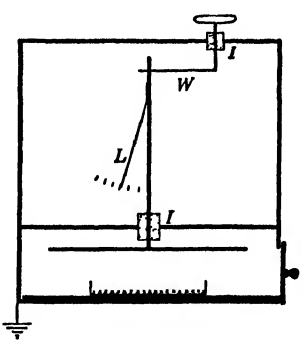


FIG. E–2. An alpha ray electroscope of large capacity.

entirely enclosed in the metal box and the ionization chamber is in a separate compartment. The leaf is charged by means of the light wire *W* which is then rotated to touch the grounded case. The insulation supports (*I*) should be of amber or sulphur, carefully scraped or cleaned to remove any conducting surfaces which would

* For further details on electroscopes see experiments 8–1 and 9–1. The preparation of metalized quartz fibers for use in fiber electroscopes is described in experiment 6–3.

greatly increase the rate at which the leaf falls when no active material is present. Ether or absolute alcohol may be used to clean amber, while sulphur and hard rubber may be scraped. The leakage is part of the so-called natural leak of the instrument. Other causes are the free ions in the air, contaminations by radioactive substances and cosmic rays.

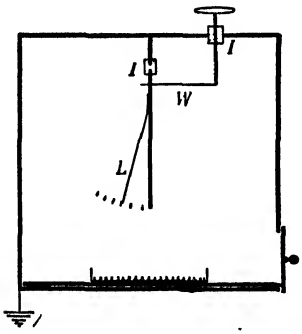


FIG. E–3. An alpha ray electroscope of small capacity.

The rate of fall of the leaf (divisions per second of the observing telescope scale) due to the natural leak must be subtracted from the rates measured when the active material is present in order to obtain the true intensity of the source. When an electroscope is first charged, the natural leak is quite large, decreases exponentially as the leaf "soaks up a charge" and is sufficiently constant that measurements may be made at the end of one-half to one hour.

For measuring feeble sources, the capacity of the leaf system with respect to the ground must be small, 2 or 3 e.s.u., as in figure E–3, while for ordinary electroscopes such as in figures 8–1 or E–1 it ranges around 10–15 e.s.u. For strong sources which would cause the leaf to fall more rapidly than desired for accurate timing, an instrument of larger capacity, figure E–2, must be used or a small condenser such as the two dotted cylinders of figure E–1 may be placed in parallel with the usual form.

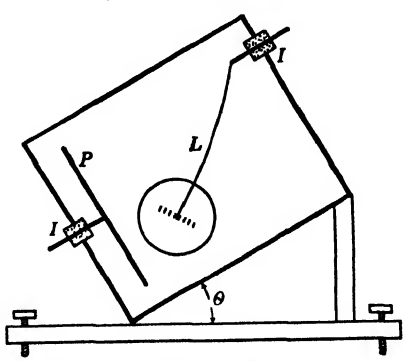


FIG. E–4. The Wilson tilted electroscope.

Figure E–4 shows the Wilson tilted electroscope, a form which is particularly sensitive because of its small capacity and the position in which the leaf is used for observation. The leaf is attracted to the charged plate *P* and takes up a position of equilibrium which approaches instability under the influence of gravity and the attraction to *P*.

The beta ray electroscopes are similar to those of figure E–1 except that an aluminum sheet about 0.006 cm. thick is placed over the active material to cut off all alpha rays. The ionization in the leaf chamber is then due to the beta and gamma rays together but the former are much better ionizers than the latter so that the fall of the leaf is largely due to the beta activity.

For measuring gamma ray activity alone, the electroscope must be built of or completely surrounded by lead two or three millimeters thick in order to cut off all alpha and beta rays. If the source is very strong, the active material may be placed several feet from the electroscope. When comparing two sources (one of which may be a standard) whose activities are quite different, each may be placed at a convenient distance so that the rate of fall of the leaf permits accurate measurement. Correction is made using the inverse square law. For example, if the rates of fall of the leaf are $R_1$ and $R_2$ when the sources are at $d_1$ and $d_2$, respectively, figure E–5, then the intensities $I_1$ and $I_2$ are in the ratio

$$\frac{I_1}{I_2} = \frac{R_1 d_2^2}{R_2 d_1^2} \qquad \text{(E–1)}$$

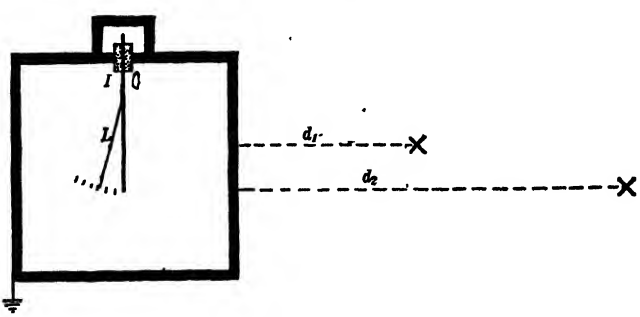


FIG. E–5. A gamma ray electroscope.

Figures E–6 and E–7 show instruments * having small capacities which are particularly useful for the study of penetrating radiations. That in figure E–6 uses fine platinized quartz fibers *LL* stretched by a quartz bow *B* and may be tipped in any desired position without materially affecting its readings. The single,

* These instruments are sometimes referred to as electrometers and as such are discussed in Appendix A.

fine, platinized-quartz fiber $L$ of figure E–7 is hung or stretched between two metal knife edges $KK$ which are usually charged to a

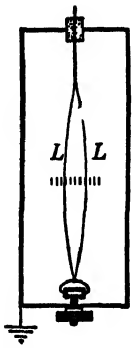


FIG. E–6. A bifilar electrometer.

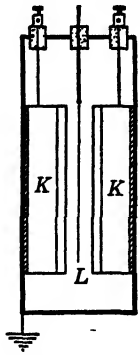


FIG. E–7. A single fiber electrometer.

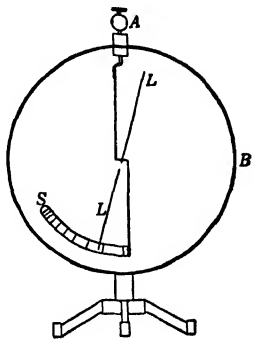


FIG. E–8. A Braun voltmeter.

high fixed potential. By using a strong source of light to cast a shadow of the fiber or fibers upon a revolving photographic plate, a continuous record of the fall of the leaf may be obtained. For long records, an automatic charging device is used to spread the fibers of E–6.

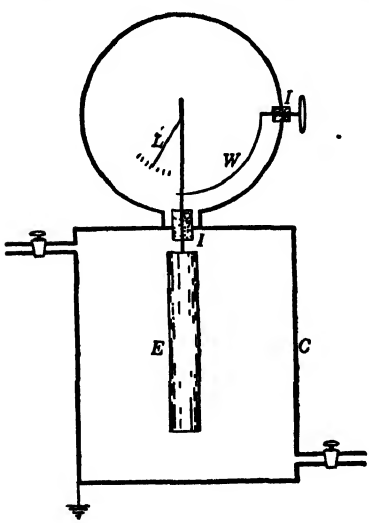


FIG. E–9. An emanation electroscope.

Figure E–8 shows a Braun voltmeter or electroscope used for rough measurements of potentials from 0 to 10,000 volts. The potential is applied between $A$ and $B$ causing the comparatively heavy aluminum needle $L$ to move over the calibrated scale $S$. The instrument does not draw any current for its operation.

For determining the activity of a gas, an *emanation* electroscope as in figure E–9 may be used. The ionization chamber $C$ is carefully cleaned and evacuated, then filled with gas. The leaf system $EL$ is charged by the wire $W$ and

draws ions of opposite sign to the collecting electrode $E$ which results in a movement of the leaf proportional to the intensity of the emanation.

Since the electroscope is essentially a potential measuring instrument, one should apply known voltages to the leaf and plot a curve of deflections vs. volts. It will be found that, at least over a limited number of scale divisions, deflections are directly proportional to the applied voltage. For accurate comparisons, the rate of fall should be observed over the same divisions.

## REFERENCES

W. MAKOWER AND H. GEIGER, *Practical Measurements in Radioactivity*, Chapter II.

See references, Appendix A, on Electrometers.

## PROBLEMS

1. In Erickson's method of measuring mobilities, ions of mobility 1.87 cm-per-sec. per volt-per-cm. are introduced into an air stream whose velocity is 1704 cm. per sec. What voltage must be applied to the parallel plates, which are 10 cm. apart, in order that the ions shall be deflected 9.0 cm. vertically while being carried a distance of 16.4 cm. by the air? (*5000 volts*)

. . . . .

2. What voltage is needed to balance an oil drop carrying 5 electrons when located between the plates of a condenser which are 5 mm. apart? The mass of the oil drop is $3.119 \times 10^{-13}$ grams. (*19.2 volts*)

3. What is the velocity of fall of an oil drop of density 0.98 and radius $10^{-4}$ cm. in air of viscosity 0.0001826 and pressure 76 cm. of mercury. Use both the corrected and uncorrected laws of fall.
(*Corrected 0.0126 cm./sec. Uncorrected 0.0117 cm./sec.*)

4. 31.5 volts applied to two parallel plates 1 cm. apart give a charged oil drop between them an upward velocity of 10 divisions in 10 seconds (50 divisions = 1 mm.). The drop falls freely under gravity with a velocity of 10 divisions in 100 seconds. The coefficient of viscosity of air = 0.00018. Density of the drop = 0.9. Neglect the density of air. Pressure = 76 cm. Hg. How many electrons does the drop carry?
(*one*)

. . . . .

5. What will be the root-mean-square value of the fluctuating current in the inductance-capacitance circuit in the plate circuit, as in the shot effect, if the effective resistance of the coils is 5 ohms, the capacity is 600 micro-microfarads and the plate current is 5 milliamperes?
(0.364 microamperes)

6. If the work function for tungsten is 4.71 volts, how many ergs of work are needed to remove an electron from its surface?
($7.49 \times 10^{-12}$ *ergs*)

7. Compute the constant $a'$ (equation 3–1) in Richardson's equation if the emission from each square centimeter of a tungsten filament at 2000° absolute is 4.2 milliamperes. The work function of tungsten is 4.71 volts. ($6.69 \times 10^{7}$)

8. Compute the constant in the Child-Langmuir equation when the limited current is 5.627 milliamperes, the plate potential being 180 volts.
($2.32 \times 10^{-6}$)

9. How many ergs of work are needed to remove an electron from the surface of sodium metal whose photo-electric long wave-length limit is 6800 angstroms? (*Greater than* $2.89 \times 10^{-12}$ *ergs* = *1.82 volts*)

10. What potential must be applied across two zinc plates when one of them is illuminated by light of wave-length 2536 angstroms in order to repel the fastest electrons ejected? The work function of zinc is 3.89 volts. (*0.987 volts*)

11. 1,000 volts is applied to the plate of a two-electrode tube. What is the velocity of the electrons when they reach the plate? ($1.88 \times 10^9$ *cm./sec.*)

12. A field of 25 gauss is applied perpendicularly to a cathode ray whose electrons have a velocity of $1.88 \times 10^9$ cm. per sec. What will be the radius of the circle into which they will be bent? (*4.25 cm.*)

13. What accelerating voltage is needed to give cathode particles a velocity of $3.763 \times 10^9$ cm. per second? (*4,000 volts*)

14. What voltage is needed to return the spot of light in Thomson's $e/m$ experiment to its original position if the magnetic field is of strength 30 gauss, the velocity of the electrons $2.66 \times 10^9$ cm. per sec. and the plates 1 cm. apart? (*798 volts*)

15. One ampere is passed through a single turn of wire of radius 13 cm. Compute the field intensity at a point 6.5 cm. off the axis and 3 cm. out from the center of the coil. Compare with the intensity on the axis at the same distance out and at the center of the coil. (*0.051, 0.045, 0.048 gauss*)

16. Compute the ratio of the masses of two electrons accelerated with 4,000 and 1,000 volts, respectively. (*1.006*)

17. Compute the mass of an electron and of the hydrogen ion in solution. ($8.99 \times 10^{-28}$ *gr.*, $1.66 \times 10^{-24}$ *gr.*)

18. Calculate the force on the plate of a two-electrode tube when bombarded by electrons accelerated by 200 volts, the plate current being 6 milliamperes and $e/m = 1.77 \times 10^7$ e.m.u./gram, assuming that all of their momentum is given up when they strike the plate. (*0.029 dynes*)

19. What wave-length is to be associated with an electron of velocity $9 \times 10^9$ cm. per sec. to give its observed diffraction pattern? Include the relativity correction for mass. (*0.077* Å)

20. Calculate the constant relating the wave-length of an electron in angstroms with its accelerating potential in volts. Neglect the relativity correction. ($\lambda = 12.25/\sqrt{V}$)

21. What wave-length is to be associated with an electron accelerated by 50,000 volts to give its observed diffraction pattern? Neglect the relativity correction. (*0.055* Å)

22. The wave-length associated with an electron is measured from the space lattice of a nickel crystal and found to be 0.0566 angstroms. The electrons were accelerated by 46,500 volts. Compute Planck's constant, assuming the mass of the electrons to be $9.0 \times 10^{-28}$ grams and neglecting the relativity correction. ($6.55 \times 10^{-27}$ *erg-sec.*)

23. Compute the intercepting cross-section (radius in cm.) of neon atoms at 0.1 mm. pressure and 0° C. when a beam of electrons in passing through 10 cm. is reduced to 0.208 of its original value. ($1.18 \times 10^{-8}$ *cm.*)

. . . . .

24. A change of 10 volts in the plate potential of a three-electrode tube causes a change of 0.833 milliamperes in its plate current. Compute the plate resistance of the tube. (*12,000 ohms*)

25. The mutual conductance of a three-electrode tube is 675 micromhos and the plate resistance is 12,000 ohms. What is the amplification constant? (*8.1*)

26. How many volts change on the grid of a three-electrode tube whose amplification constant is 8 and plate resistance is 12,000 ohms are needed to change the plate current by 4.0 milliamperes? (*6 volts*)

27. The ionizing potential of helium is 24.5 volts. What energy in ergs is required to extract an electron from its normal position in the atom? ($3.90 \times 10^{-11}$ *ergs*)

28. Compute the constant relating radiation potentials in volts and the wave-length of the emitted light in angstrom units. ($V = 12344/\lambda$)

. . . . .

29. The mean free path of nitrogen molecules at a pressure of 76 cm. and temperature of 0° C. is $950 \times 10^{-8}$ cm. What is the mean free path at a pressure of 0.001 mm. of mercury and temperature 0° C.? (*7.22 cm.*)

30. A discharge tube containing pure argon is placed in a horizontal position and viewed with a rotating mirror whose axis of rotation is parallel to the axis of the tube. The mirror rotates at 2400 r.p.m. and the striations are seen to be inclined at an angle of 56 degrees with

the axis of the tube when viewed at a distance of 30 cm. from the mirror. What is the velocity of the striations? (*10,170 cm./sec.*)

31. If hydrogen positive rays continue to radiate light 4 cm. beyond the cathode and the red spectrum line (6563 angstroms) has a Doppler shift of 2.188 angstroms, what is the time duration of the light emission? ($4 \times 10^{-7}$ *sec.*)

. . . . .

32. What is the mass of the alpha particle in grams? ($6.60 \times 10^{-24}$ *gr.*)

33. The ranges of the alpha particles from radium A and radium C′ are 4.50 cm. and 6.57 cm. respectively. If the velocity of those from radium A is $1.695 \times 10^9$ cm. per sec., what is the velocity of those from radium C′? ($1.923 \times 10^9$ *cm./sec.*)

34. Compute the constants relating the range with the transformation constant for the uranium series. See table for figure 7–13, page 100. (*Averaged values* $A = -30.8$, $B = 55.3$)

35. The range of the alpha particles from radium A is 5.00 cm. at 74 cm. mercury pressure and 22.7° C. What will the range be at 76 cm. and 0° C.? (*4.50 cm.*)

36. Compute the wave-length of the "modified line" of an X-ray beam whose wave-length is 0.558 Å ($K_{\alpha 1}$ line of silver). The scattered rays are observed at an angle of 46° with the direction of the primary beam. (*0.565Å*)

. . . . .

37. The absorption coefficients of beta rays in aluminum for uranium $X_1$ and uranium $X_2$ are 463 and 14.4, respectively. What thicknesses of aluminum are necessary to reduce each to one one-hundredth of the original intensity? (*0.00995 cm. for* $UX_1$; *0.320 cm. for* $UX_2$)

38. The coefficient of absorption of a gamma ray is proportional to the density of the absorbing material. What thickness of cast iron will reduce the intensity of a gamma ray by the same amount as one inch of lead? (*1.61 in.*)

39. The absorption coefficients of beta rays in aluminum for radium C are 13.2 and 53. What will be the reduction in intensity of the *more* penetrating of these rays when passed through a sheet of aluminum which reduces the *less* penetrating to one one-hundredth of the original value? (*68.2 per cent*)

40. What percentage of beta rays from uranium $X_2$ and of gamma rays from radium C will penetrate 0.12 cm. of aluminum whose absorption coefficients for these rays are 14.4 and 0.115 respectively? (*17.8 per cent, 98.6 per cent*)

41. 47.97 cm. of aluminum will reduce the gamma rays from thorium $C''$ to one one-hundredth of their original value. What is the coefficient of absorption? (*0.096*)

42. The half life period of thorium is $1.31 \times 10^{10}$ years. What is its transformation constant and average life?
(*$1.68 \times 10^{-18}$ per sec., $1.89 \times 10^{10}$ years*)

43. How many days after uranium $X_1$ has been isolated before 90 per cent has changed to uranium $X_2$? The half period of uranium $X_1$ is 24.6 days. (*81.7 days*)

44. The transformation constant for radium is $1.30 \times 10^{-11}$ per second and its atomic weight is 226. The atomic weight of uranium I is 238. There are $3.44 \times 10^{-7}$ grams of radium in equilibrium with each gram of uranium I. Calculate the half period of uranium I in years. (*$4.67 \times 10^{9}$ years*)

45. One gram of radium emits $3.45 \times 10^{10}$ alpha particles per second. The transformation constant of radium emanation is $2.085 \times 10^{-6}$ atoms per second and its density is 0.00987 gr. per c.c. The number of atoms per c.c. of a monatomic gas is $2.705 \times 10^{19}$. Calculate the volume and mass of one curie. (*0.61 mm.$^3$; $6.04 \times 10^{-6}$ gr.*)

46. There are $13.6 \times 10^{10}$ alpha particles emitted each second by one gram of radium in equilibrium with its decay products. Calculate the volume of helium produced by one gram of radium and its products in one year. (*159 mm.$^3$*)

47. The number of alpha particles emitted per gram of radium each second is $3.45 \times 10^{10}$. If the atomic weight of radium is 226, what is its half period in years? Take 365.25 days in the year. (*1708 years*)

48. Uranium I is freed from all its products and placed in a beta-ray electroscope. How many days before the rate of fall of the leaf of the electroscope reaches 50% of its maximum value? The transformation constant of uranium $X_1$ is $3.26 \times 10^{-7}$. (24.6 days.)

49. If a person has one gram of radium today, how much will he have at the end of 10 years? Take the half life of radium as 1690 years. (*0.9959 gr.*)

50. The voltage sensitivity of a quadrant electrometer is 1,000 scale divisions per volt. Its capacity is 50 e.s.u. A certain current causes a motion of 0.1 divisions per second. What is the value of this current in amperes? (*$5.56 \times 10^{-15}$ amps*)

51. The voltage sensitivity of a quadrant electrometer is 600 divisions per volt and its capacity is 100 e.s.u. What charge, in coulombs, must be added to the system in order to produce a deflection of 20 divisions? (*3.70 × 10⁻¹² coulombs*)

52. Derive the relation between the pressure units, i.e., the mm. of mercury and the bayre. Take $g = 980.616$ and the density of mercury at 20° C. (*1 mm. = 1328 bayres*)

53. The volume of a McLeod gauge bulb and capillary is 314.16 c.c. and the radius of its capillary is 1.0 mm. The mercury is raised so that in the central capillary it is 10 cm. below the top of the tube and 20 cm. below the mercury in the other capillary. What is the pressure of the gas in the system? (*0.2 mm.*)

54. The positive ion current in an ionization gauge is $5 \times 10^{-6}$ milliamperes when the pressure is $10^{-3}$ mm. of Hg. What is the pressure when this current is $5 \times 10^{-8}$ milliamperes? ($10^{-5}$ *mm.*)

55. In a vacuum system it is desired to double the flow of gas through the glass tubing. Other conditions remaining the same, the length is reduced by 20 per cent. What change must be made in the radius of the tubing? (*Increased in ratio 1.17/1.00*)

56. The voltage sensitivity of an electroscope is 200 divisions per volt. Its capacity is 2 e.s.u. A certain current moves the leaf at the rate of 0.1 divisions per second. What is the value of this current in amperes? (*1.11 × 10⁻¹⁵ amps*)

57. The leaf of an electroscope is found to pass over 10 divisions in 10 seconds when a radioactive substance is nearby. A standard condenser is placed in parallel with the instrument. The leaf then takes 50 seconds to pass over the same number of divisions. The standard condenser is made of two concentric cylinders of length 10 cm. The outside diameter of the inner cylinder is 2 cm. and the inside diameter of the outer one is 3 cm. What is the capacity of the electroscope? (*3.08 e.s.u.*)

58. In what ways does the passage of electricity through a gas differ from metallic conduction?

59. State as many general laws of radioactivity as you can recall.

60. What proof is there: that there are comparatively large spaces free from matter in the atoms; that the nucleus of an atom is comparatively small; that the atomic number is equal to the charge on the nucleus; that electricity is granular; that there is a wave-length associated with an electron; that the emission of electricity from a hot filament is

analogous to the evaporation of a liquid; that the mass of an electron changes with its velocity; that alpha particles are the nuclei of heliun atoms; that certain elements are spontaneously changing from one into another; that atoms and molecules are constantly moving about; that cosmic rays come from beyond the earth; that the same fraction of atoms of a radioactive substance break up each second; that alpha particles travel in straight lines whereas beta particles follow a tortuous path; that cathode rays are electrons; that hydrogen nuclei can be knocked out of a great many elements.

## TABLE 1. — SOME IMPORTANT CONSTANTS

*R. T. Birge, Physical Review Supplement, July* 1929.

| | | | |
|---|---|---|---|
| Velocity of light | $c$ | $2.99796 \times 10^{10}$ | cm. per sec. |
| Atomic weight of hydrogen | | 1.00777 | |
| helium | | 4.0022 | |
| oxygen | | 16.0000 | (By definition) |
| silver | | 107.880 | |
| Faraday constant | $F$ | 96,489 | abs. coulombs/g. |
| | | 96,494 | int. coulombs/g. |
| Electron charge | $e$ | $4.770 \times 10^{-10}$ | abs. e.s.u. |
| | | $1.5911 \times 10^{-20}$ | abs. e.m.u. |
| Electron charge/mass | $\frac{e}{m}$ | $1.761 \times 10^{7}$ | e.m.u./gram * |
| | | $1.769 \times 10^{7}$ | e.m.u./gram † |
| Electron mass | $m_0$ | $9.035 \times 10^{-28}$ | grams * |
| | | $8.994 \times 10^{-28}$ | grams † |
| Mass hydrogen atom | $M_H$ | $1.6618 \times 10^{-24}$ | grams |
| Mass of an atom of unit atomic weight | $M_0$ | $1.6490 \times 10^{-24}$ | grams |
| Hydrogen ion, charge/mass | $e/M_H$ | 9,574.5 | abs. e.m.u./g. |
| Ratio of mass, $H$ ion to electron | | 1839 | (Spectroscopic) |
| | | 1848 | (Deflection) |
| Planck's constant | $h$ | $6.547 \times 10^{-27}$ | erg-sec. |
| Gas constant | $R_0$ | $8.3136 \times 10^{7}$ | erg/degree/mole. |
| Boltzmann's constant | $k$ | $1.3709 \times 10^{-16}$ | erg/degree |
| Avogadro's number | $N_0$ | $6.064 \times 10^{23}$ | per mole. |
| Loschmidt's number (0°C., $A_n$) | $n_0$ | $2.705 \times 10^{19}$ | per cm.$^3$ |
| *From various sources* | | | |
| Alpha particles per second: from one gram of radium; | | $3.45 \times 10^{10}$ | per sec. |
| from one gram of radium in equilibrium with its short life products | | $13.8 \times 10^{10}$ | per sec. |
| Alpha particle charge/mass | | 4823 | e.m.u./g. |
| Alpha particle charge | | $9.54 \times 10^{-10}$ | e.s.u. |
| Electrochem. equiv. of silver | | 0.00111800 | g. per coulomb |

* Spectroscopic. † Deflection.

## TABLE 2. — SPARKING POTENTIALS

The voltages given are *peak values* (not the usual root-mean-square voltages) which will just break down non-ionized air at a pressure of 760 mm. and temperature 25° C. Needle gap voltages at a relative humidity of 80%. Sphere gap values practically independent of humidity. Adapted from values in the Handbuch der Physik (Geiger and Scheel), Vol. 16, p. 407, 1927. 1 and 2 cm. sphere values from Kaye "X-rays," p. 102, 1923.

| Gap in *Cm.* | Kilovolts. A = Electrodes ungrounded B = One electrode grounded | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Needle Points *A* | Diameter of Spheres | | | | | | | | | |
| | | 1 *cm* | 2 *cm* | 6.25 *cm* | | 12 5 *cm* | | 25.0 *cm* | | 50.0 *cm* | |
| | | *A* | *A* | *A* | *B* | *A* | *B* | *A* | *B* | *A* | *B* |
| 0.25 | 3 | 10 | 10 | 9 | 9 | 9 | 9 | | | | |
| 0.50 | 5 | 17 | 17 | 17 | 17 | 17 | 17 | | | | |
| 1.00 | 12 | 27 | 31 | 33 | 33 | 33 | 33 | | | | |
| 1.50 | 17 | 32 | 40 | 45 | 45 | 45 | 45 | | | | |
| 2.0 | 23 | 36 | 48 | 59 | 59 | 59 | 59 | 60 | 60 | 60 | 60 |
| 3.0 | 33 | 42 | 58 | 82 | 79 | 85 | 85 | 86 | 86 | 86 | 86 |
| 4.0 | 42 | 45 | 65 | 100 | 93 | 109 | 109 | 91 | 91 | 93 | 93 |
| 5.0 | 49 | 47 | 71 | 114 | 103 | 131 | 130 | 139 | 139 | 140 | 136 |
| 6.0 | 56 | | 77 | 127 | 111 | 151 | 147 | 163 | 160 | 164 | 163 |
| 7.0 | 61 | | | | | 169 | 159 | 184 | 182 | 192 | 188 |
| 8.0 | 66 | | | | | 185 | 171 | 206 | 203 | 218 | 214 |
| 9.0 | 71 | | | | | 200 | 181 | 226 | 222 | 243 | 238 |
| 10.0 | 75 | | | | | 214 | 191 | 245 | 240 | 269 | 264 |
| 12.0 | | | | | | 237 | 208 | 278 | 272 | 318 | 312 |
| 15.0 | | | | | | | 226 | 325 | 311 | 381 | 371 |
| 17.5 | | | | | | | | 362 | 338 | 432 | 420 |
| 20.0 | | | | | | | | 392 | 360 | 475 | 461 |
| 22.5 | | | | | | | | 418 | 379 | 515 | 497 |
| 25.0 | | | | | | | | 440 | 396 | 555 | 531 |
| 30.0 | | | | | | | | 480 | 425 | 633 | 598 |

TABLE 3. — WORK FUNCTIONS AND PHOTOELECTRIC LONG WAVE-LENGTH LIMITS

| Substance | Work Functions in Volts | | Long Wave limit in $A^\circ$ |
|---|---|---|---|
| | Thermionic | Photoelectric | |
| •Platinum | 6.27 | 6.30 | 1962 |
| with BaO 50% SrO 50% | 1.97–2.22 | | |
| with BaO 50% SrO 25% CaO 25% | 2.39–2.54 | | |
| with CaO | 3.22–3.51 | | |
| Tungsten | 4.71 | 4.79 | 2575 |
| Calcium | | 2.76 | 4475 |
| Iron | | 3.91 | 3155 |
| Cobalt | | 3.90 | 3165 |
| Nickel | | 4.06 | 3040 |
| Copper | | 4.18 | 2955 |
| Zinc | | 3.89 | 3180 |
| Mercury | | | 2735 |

## TABLE 4. — SOME VACUUM TUBE CONSTANTS

*Values From E. T. Cunningham Inc. May 1, 1929*

| Type | Use | $E_f$ Filament Terminal Volts | $I_f$ Filament Current Amperes | $E_p$ "B" Plate Volts | $E_g$ "C" Grid Volts | $I_p$ Plate Current Milliamperes | $r_p$ A.C. Plate Resistance Ohms | $g_m$ Mutual Conductance Micro-mhos | $\mu$ Voltage Amplification Factor | Maximum Undistorted Output Milliwatts |
|---|---|---|---|---|---|---|---|---|---|---|
| CX12 | Detector, Amplifier | 1.1 | .25 | 90 | 4.5 | 2.5 | 15,500 | 425 | 6.6 | 7 |
| | | | | 135 | 10.5 | 3.5 | 15,000 | 440 | 6.6 | 35 |
| CX299 UX199 | Detector or Amplifier | 3.3 | .063 | 45 | 1.5 | 1.0 | 19,500 | 320 | 6.6 | |
| | | | | 67.5 | 3.0 | 1.7 | 16,500 | 380 | 6.6 | |
| | | | | 90 | 4.5 | 2.5 | 15,500 | 425 | 6.6 | 7 |
| CX220 UX120 | Power Amplifier | 3.3 | .132 | 90 | 16.5 | 3.2 | 7,700 | 428 | 3.3 | |
| | | | | 135 | 22.5 | 6.5 | 6,600 | 500 | 3.3 | 110 |
| CX322 UX222 | Screen Grid Amplifier [1] | 3.3 | .132 | 90 | 1.5 | 1.4 | 500,000 | 340 | 175 | |
| | | | | 135 | 1.5 | 1.5 | 850,000 | 350 | 290 | |
| | | | | 135 | 3.0 | 1.0 | 1,100,000 | 280 | 300 | |
| CX300A UX200A | Special Detector | 5.0 | .25 | 45 | | 1.5 | 30,000 | 670 | 20 | |
| CX301A UX201A | Detector or Amplifier | 5.0 | .25 | 45 | 1.5 | 0.9 | 18,500 | 430 | 8.0 | |
| | | | | 67.5 | 3.0 | 1.7 | 14,000 | 570 | 8.0 | |
| | | | | 90 | 4.5 | 2.5 | 11,000 | 725 | 8.0 | 15 |
| | | | | 135 | 9.0 | 3.0 | 10,000 | 800 | 8.0 | 55 |
| CX340 UX240 | Detector or Amplifier | 5.0 | .25 | 135 | 1.5 | 0.2 | 150,000 | 200 | 30 | |
| | | | | 180 | 3 0 | 0.2 | 150,000 | 200 | 30 | |
| CX326 UX226 | Amplifier | 1.5 | 1.05 | 90 | 6 0 | 3.7 | 9,400 | 875 | 8.2 | 20 |
| | | | | 135 | 9 0 | 6.0 | 7,400 | 1,100 | 8.2 | 70 |
| | | | | 180 | 13.5 | 7.5 | 7,000 | 1,170 | 8.2 | 160 |
| C327 UY227 | Detector or Amplifier | 2.5 | 1.75 | 45 | 0 | .... | 8,500 | 1,050 | 9.0 | |
| | | | | 90 | 6.0 | 3.0 | 10,000 | 900 | 9.0 | |
| | | | | 135 | 9.0 | 5.0 | 9,000 | 1,000 | 9.0 | |
| | | | | 180 | 13.5 | 6.0 | 9,000 | 1,000 | 9.0 | |
| C324 UY224 | A.C. Screen Grid Amplifier [2] | 2.5 | 1.75 | 180 | 1.5 | 4.0 | 400,000 | 1,050 | 420 | |
| CX112A UX112A | Power Amplifier | 5.0 | .25 | 90 | *4.5 | 5.5 | 5,300 | 1,500 | 8.0 | 30 |
| | | | | 135 | 9.0 | 7.0 | 5,000 | 1,600 | 8.0 | 120 |
| | | | | 157.5 | 10.5 | 9.5 | 4,700 | 1,700 | 8.0 | 195 |
| | | | | 180 | 13.5 | 9.5 | 4,700 | 1,700 | 8.0 | 300 |
| CX371A UX171A | Power Amplifier | 5.0 | .25 | 90 | *16.5 | 10.0 | 2,500 | 1,200 | 3.0 | 130 |
| | | | | 135 | 27.0 | 16.0 | 2,200 | 1,360 | 3.0 | 330 |
| | | | | 157 | 33.0 | 18.0 | 2,150 | 1,400 | 3.0 | 500 |
| | | | | 180 | 40.5 | 20.0 | 2,000 | 1,500 | 3.0 | 700 |
| CX345 UX245 | Power Amplifier | 2.5 | 1.5 | 180 | 33.0 | 26.0 | 1,950 | 1,800 | 3.5 | 780 |
| | | | | 350 | 50.0 | 32.0 | 1,900 | 1,850 | 3.5 | 1,600 |
| CX310 UX210 | Power Amplifier Oscillator | 7.5 | 1.25 | 250 | *18.0 | 10.0 | 6,000 | 1,330 | 8.0 | 340 |
| | | | | 350 | 27.0 | 16.0 | 5,150 | 1,550 | 8.0 | 925 |
| | | | | 425 | 35.0 | 18.0 | 5,000 | 1,600 | 8.0 | 1,540 |
| CX350 UX250 | Power Amplifier | 7.5 | 1.25 | 250 | 45 | 28.0 | 2,100 | 1,800 | 3.8 | 900 |
| | | | | 300 | 54 | 35.0 | 2,000 | 1,900 | 3.8 | 1,500 |
| | | | | 350 | 63 | 45.0 | 1,900 | 2,000 | 3.8 | 2,350 |
| | | | | 400 | 70 | 55.0 | 1,800 | 2,100 | 3.8 | 3,250 |
| | | | | 450 | 84 | 55.0 | 1,800 | 2,100 | 3.8 | 4,650 |
| CX380 UX280 | Full wave Rectifier | 5.0 | 2.0 | Max. A.C. per plate 350 | | Max. rectified 125 | | | | |
| CX381 UX281 | Half wave Rectifier | 7.5 | 1.25 | Max. A.C. 700 r.m.s. | | Max. rectified 85 | | | | |

* If filament current is A.C., increase values given by one-half the filament voltage.

[1] Screen grid at +45 volts.

[2] Screen grid at +75 volts.

TABLE 5. — CRITICAL POTENTIALS

| Substance | | $V_i$ Ionizing Potential in volts | Resonance | | $V_r$ Minimum Radiation | |
|---|---|---|---|---|---|---|
| | | | Potential in volts | Angstroms | Potential in volts | Angstroms |
| Hydrogen atom | H | 13.54 | 10.15 | 1216 | 10.15 | 1216 |
| Hydrogen molecule | $H_2$ | 16.1 | 11.5 | No Radiation Meta-stable | 11.57 | 1066 |
| Helium Atom | He | 24.5 | 19.77 | No Radiation Meta-stable | 21.12 | 584 |
| Nitrogen molecule | $N_2$ | 16.9 | 8.2? | No Radiation Meta-stable | 8.5 | 1452 |
| Oxygen molecule | $O_2$ | 13.5? (12.6–16) | ? | ..... | 6.1 | 2025 |
| Neon atom | Ne | 21.5 | 16.6 | 744 | 16.6 | 744 |
| Argon atom | A | 15.4 | 11.5 | 1066 | 11.5 | 1066 |
| Mercury atom | Hg | 10.39 | 4.66 | No Radiation Meta-stable | 4.86 | 2537 |

## TABLE 6. — RANGE AND VELOCITY OF ALPHA RAYS

Range in cm. at 0° C., 760 mm. of mercury. Velocity in cm. per sec.

*From the International Critical Tables, Vol. I, p. 363. McGraw Hill Book Co., Publishers.*

| Substance | Symbol | Range | Velocity |
|---|---|---|---|
| Uranium I | UI | 2.37 | $1.368 \times 10^9$ |
| Uranium II | UII | 2.75 | 1.437 " |
| Ionium | Io | 2.85 | 1.455 " |
| Radium | Ra | 3.13 | 1.500 " |
| Radon (Emanation) | Rn | 3.94 | 1.620 " |
| Radium A | Ra-A | 4.50 | 1.695 " |
| Radium C′ | Ra-C′ | 6.57 | 1.923 " |
| Radium F (Polonium) | Ra-F(Po) | 3.58 | 1.569 " |
| Protoactinium | Pa | 3.314 | 1.530 " |
| Radio-actinium | Rd-Ac | 4.36 | 1.677 " |
| Actinium X | Ac-X | 4.17 | 1.650 " |
| Actinon (Emanation) | An | 5.40 | 1.800 " |
| Actinium A | Ac-A | 6.16 | 1.881 " |
| Actinium C | Ac-C | 5.12 | 1.767 " |
| Thorium | Th | 2.58 | 1.407 " |
| Radiothorium | Rd-Th | 3 67 | 1.581 " |
| Thorium X | Th-X | 4.08 | 1.638 " |
| Thoron (Emanation) | Tn | 4.74 | 1.722 " |
| Thorium A | Th-A | 5.40 | 1.800 " |
| Thorium C | Th-C | 4.55 (4.69?) | 1.716 " |
| Thorium C′ | Th-C′ | 8.16 | 2.064 " |

## TABLE 7. — ABSORPTION COEFFICIENTS AND VELOCITIES OF BETA RAYS

Absorption coefficients ($\mu$) in aluminum. Distances in cm. Velocities ($v$) are relative to that of light. Multiply by $3 \times 10^{10}$ to obtain cm. per sec.

| Substance | Symbol | $\mu$ | $v$ |
|---|---|---|---|
| Uranium $X_1$ | $UX_1$ | 463 | (continuous spectrum) |
| Uranium $X_2$ | $UX_2$ | 14.4 | (continuous spectrum) |
| Radium | Ra | 312 | 0.52; 0.65 |
| Radium B | Ra-B | 13.1; 80 | 0.36; 0.41; 0.63; 0.70; 0.74 |
| Radium C | Ra-C | 13.2; 53 | 0.786; 0.862; 0.949; 0.957 |
| Radium D | Ra-D | 5500 | 0.33; 0.39 |
| Radium E | Ra-E | 43.3 | (continuous spectrum 0.7 to 0.94) |
| Uranium Y | UY | About 300 | |
| Radioactinium | Rd-Ac | About 170 | 0.38; 0.43; 0.49; 0.53; 0.60; 0.67; |
| Actinium B | Ac-B | Very large | 0.73 |
| Actinium C″ | Ac-C″ | 28.5 | |
| Mesothorium 2 | Ms-Th 2 | 20.2 to 38.5 | 0.37; 0.39; 0.43; 0.50; 0.57; 0.60; 0.66; and $> 0.70$ |
| Radiothorium | Rd-Th | | 0.47; 0.51 |
| Thorium B | Th-B | 110 | 0.63; 0.72 |
| Thorium C + C″ | Th-C,Th-C″ | 14.4; 21.6 | 0.29; 0.36; 0.93; 0.95 |
| Potassium | K | 22 to 38 | |
| Rubidium | Rb | 308 to 347 | |

*From the International Critical Tables, Vol. I, p. 363. McGraw Hill Book Co., Publishers.*

## TABLE 8. — ABSORPTION COEFFICIENTS OF GAMMA RAYS

$\mu_{al}$ = absorption coefficient in aluminum. $\mu_{pb}$ = absorption coefficient in lead.

| Substance | Symbol | $\mu_{al}$ | $\mu_{pb}$ |
|---|---|---|---|
| Uranium $X_2$ | $UX_2$ | 24; 0.7; 0.14 | 0.72 |
| Radium | Ra | 354; 16; 0.27 | |
| Radium B | Ra-B | 230; 40; 0.51 | |
| Radium C | Ra-C | 0.115; | 0.50 |
| Radium D | Ra-D | 45; 0.99 | |
| Radium F (= Polonium) | Ra-F (= Po) | 585 | |
| Radioactinium | Rd-Ac | 25; 0.19 | |
| Actinium B | Ac-B | 120; 31; 0.45 | |
| Actinium C″ | Ac-C″ | 0.198 | 1.2 to 1.8 |
| Mesothorium 2 | Ms-Th 2 | 26; 0.116 | 0.62 |
| Thorium B | Th-B | 160; 32; 0.36 | |
| Thorium C″ | Th-C″ | 0.096 | 0.46 |

*From the International Critical Tables, Vol. I, p. 363. McGraw Hill Book Co., Publishers.*

## TABLE 9. — MASS ABSORPTION COEFFICIENTS OF X-RAYS

From Table VI, 5, p. 184, A. H. Compton. "X-rays and Electrons."

| Wave-length in Angstroms | Carbon | Aluminum | Iron | Nickel | Copper | Zinc |
|---|---|---|---|---|---|---|
| .100 | .146 | .164 | .265 | .328 | .323 | .38 |
| .125 | .152 | .178 | .399 | .475 | .49 | .60 |
| .150 | .160 | .201 | .572 | .68 | .77 | .92 |
| .175 | .162 | .231 | .79 | 1.00 | 1.10 | 1.28 |
| .200 | .170 | .269 | 1.07 | 1.40 | 1.53 | 1.77 |
| .250 | .184 | .370 | 1.93 | 2.50 | 2.75 | 3.15 |
| .300 | .197 | .531 | 3.18 | 4.10 | 4.47 | 5.10 |
| .350 | .216 | .756 | 4.94 | 6.22 | 6.91 | 7.90 |
| .400 | .240 | 1.05 | 7.17 | .... | 10.1 | 11.6 |
| .500 | .310 | 1.91 | 14.3 | 18. | 18.8 | 22.2 |
| .600 | .412 | 3.18 | 23.3 | 30. | 31.6 | 37.2 |
| .700 | .540 | 5.00 | 36.3 | 45. | 49.2 | 57.0 |
| .800 | .72 | 7.50 | 51.7 | .... | .... | .... |
| .900 | 1.00 | 10.3 | 69.6 | 82. | 97. | 107. |
| 1.00 | 1.30 | 13.8 | 95. | 118. | 133. | 152. |
| 1.10 | 2.1 | 20.0 | 126. | 159. | 181. | 188. |
| 1.40 | 4.0 | 38. | 270. | 288. | | |

## TABLE 10. — RADIOACTIVE SERIES

### Uranium — Radium Series

| Substance | Atomic Weight | Atomic No. | Symbol | Radiation | Half Period T |
|---|---|---|---|---|---|
| Uranium I | 238 | 92 | U I | $\alpha$ | $4\ 67 \times 10^9$ yrs. |
| Uranium $X_1$ | 234 | 90 | U-$X_1$ | $\beta$ | 24.6 days |
| Uranium $X_2$ | 234 | 91 | U-$X_2$ | $\beta(\gamma)$ | 1.15 min. |
| Uranium II | 234 | 92 | U II | $\alpha$ | $2 \times 10^6$ yrs. |
| Ionium | 230 | 90 | Io | $\alpha$ | $6\ 9 \times 10^4$ yrs. |
| Radium | 226 | 88 | Ra | $\alpha(\beta+\gamma)$ | 1690 yrs. |
| Radon (Emanation) | 222 | 86 | Rn | $\alpha$ | 3.85 days |
| Radium A | 218 | 84 | Ra-A | $\alpha$ | 3 min. |
| Radium B | 214 | 82 | Ra-B | $\beta(\gamma)$ | 26.8 min. |
| Radium C | 214 | 83 | Ra-C | 99 97% $\beta+\gamma \rightarrow$ C′<br>0 03% $\alpha \rightarrow$ C″ | 19.5 min. |
| Radium C′ | 214 | 84 | Ra-C′ | $\alpha$ | $10^{-4}$ sec. |
| {Radium C″ | 210 | 81 | Ra-C″ | $\beta$ | 1.4 min. |
| {Radium Ω″(?) | 210 | 82 | RaΩ″ | | ∞ |
| Radium D | 210 | 82 | Ra-D | $(\beta+\gamma)$ | 16 5 yrs. |
| Radium E | 210 | 83 | Ra-E | $\beta$ | 5 0 days |
| Radium F (= Polonium) | 210 | 84 | Ra-F (= Po) | $\alpha(\gamma)$ | 136. days |
| Radium Ω′ (= Lead) | 206 · | 82 | RaΩ′ Pb206) | | ∞ |

### Actinium Series

| Substance | Atomic Weight | Atomic No. | Symbol | Radiation | Half Period |
|---|---|---|---|---|---|
| Uranium? | ? | 92 | U | $\alpha$ | |
| Uranium Y | ? | 90 | UY | $\beta$ | 1.04 days |
| Protoactinium | ? | 91 | Pa | $\alpha$ | $1\ 2 \times 10^4$ yrs. |
| Actinium | ? | 89 | Ac | | 20 yrs. |
| Radioactinium | ? | 90 | Rd-Ac | $\alpha(\beta)$ | 19.5 days |
| Actinium X | ? | 88 | Ac-X | $\alpha$ | 11 4 days |
| Actinon (Emanation) | ? | 86 | An | $\alpha$ | 3 9 sec. |
| Actinium A | ? | 84 | Ac-A | $\alpha$ | $2\ 0 \times 10^{-3}$ sec. |
| Actinium B | ? | 82 | Ac-B | ($\beta$ and $\gamma$) | 36 1 min |
| Actinium C | ? | 83 | Ac-C | $\alpha$ | 2.15 min |
| Actinium C″ | ? | 81 | Ac-C″ | $\beta$ and $\gamma$ | 4.71 min. |
| Actinium Ω″ ? | ? | 82 | AcΩ″ | | ∞ |

### Thorium Series

| Substance | Atomic Weight | Atomic No. | Symbol | Radiation | Half Period |
|---|---|---|---|---|---|
| Thorium | 232 | 90 | Th | $\alpha$ | $1.31 \times 10^{10}$ yrs. |
| Mesothorium 1 | 228 | 88 | Ms-Th1 | | 6.7 yrs. |
| Mesothorium 2 | 228 | 89 | Ms-Th2 | $\beta$ and $\gamma$ | 6.2 hrs. |
| Radiothorium | 228 | 90 | Rd-Th | $\alpha(\beta)$ | 2.02 yrs. |
| Thorium X | 224 | 88 | Th-X | $\alpha$ | 3.64 days |
| Thoron (Emanation) | 220 | 86 | Tn · | $\alpha$ | 54 sec. |
| Thorium A | 216 | 84 | Th-A | $\alpha$ | 0.14 sec. |
| Thorium B | 212 | 82 | Th-B | $\beta$ and $\gamma$ | 10.6 hrs. |
| Thorium C | 212 | 83 | Th-C | 65% $\beta \rightarrow$ C′<br>35% $\alpha \rightarrow$ C″ | 60 min. |
| Thorium C′ | 212 | 84 | Th-C′ | $\alpha$ | $10^{-11}$ sec. |
| Thorium C″ | 208 | 81 | Th-C″ | $\beta$ and $\gamma$ | 3.1 min. |
| Thorium Ω′(Lead) | 208 | 82 | ThΩ′(Pb) | | ∞ |
| Thorium Ω″(Lead) | 208 | 82 | ThΩ″(Pb) | | ∞ |
| Potassium | 39.1 | 19 | K | $\beta$ | |
| Rubidium | 85.5 | 37 | Rb | $\beta$ | |

*From the International Critical Tables, Vol. I, p. 363. McGraw Hill Book Co., Publishers.*

## TABLE 11. — ELECTRON VELOCITIES AT VARIOUS ACCELERATING POTENTIALS

Values calculated using the relativity equation

$$m_0c^2\left(\frac{1}{\sqrt{1-v^2/c^2}}-1\right)=\frac{Ve}{300}$$

where $V$ = volts, $v$ = velocity in cm. per sec. $e/m_0 = 1.77 \times 10^7$ e.m.u./gr., $c = 2.998 \times 10^{10}$ cm./sec. The deviations from non-relativistic velocities ($\frac{1}{2}mv^2 = Ve/300$) are negligible to 300 volts, not over ½% (smaller) to 3,000 volts and not over 1 % (smaller) to 7,000 volts.

| Volts | $\beta = \frac{v}{c}$ | Velocity, $\times 10^{10}$ = cm/sec. | Volts | $\beta = \frac{v}{c}$ | Velocity, $\times 10^{10}$ = cm/sec. |
|---|---|---|---|---|---|
| 1 | .001984 | .00595 | 5,000 | .1393 | .418 |
| 5 | .004438 | .0133 | 6,000 | .1523 | .457 |
| 10 | .006266 | .0188 | 7,000 | .1644 | .493 |
| 20 | .008875 | .0266 | 8,000 | .1754 | .526 |
| 30 | .01087 | .0326 | 9,000 | .1858 | .557 |
| 40 | .01255 | .0376 | 10,000 | .1956 | .586 |
| 50 | .01403 | .0421 | 20,000 | .2727 | .817 |
| 60 | .01537 | .0461 | 30,000 | .3293 | .987 |
| 70 | .01660 | .0498 | 40,000 | .3751 | 1.12 |
| 80 | .01774 | .0532 | 50,000 | .4138 | 1.24 |
| 90 | .01883 | .0564 | 60,000 | .4474 | 1.34 |
| 100 | .01984 | .0595 | 70,000 | .4771 | 1.43 |
| 200 | .02806 | .0841 | 80,000 | .5037 | 1.51 |
| 300 | .03436 | .103 | 90,000 | .5277 | 1.58 |
| 400 | .03967 | .119 | 100,000 | .5486 | 1.64 |
| 500 | .04434 | .133 | 200,000 | .6966 | 2.09 |
| 600 | .04857 | .146 | 300,000 | .7777 | 2.33 |
| 700 | .05245 | .157 | 400,000 | .8289 | 2.49 |
| 800 | .05607 | .168 | 500,000 | .8638 | 2.59 |
| 900 | .05946 | .178 | 600,000 | .8888 | 2.66 |
| 1,000 | .06267 | .188 | 700,000 | .9073 | 2.72 |
| 2,000 | .08849 | .265 | 800,000 | .9215 | 2.76 |
| 3,000 | .1082 | .324 | 900,000 | .9326 | 2.80 |
| 4,000 | .1248 | .374 | 1,000,000 | .9416 | 2.82 |

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